CE 203

Engineering Geology & Geomorphology

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Room No. 631, Civil Building

- Two Classes per week
- Three Class Tests
- Assignments
- If you have questions, you are welcome to have discussions after class hours

Acknowledgement:

- Text Books
- Various Internet Sources

Reference Materials:

- Class Lecture
- Class Handouts
- Text Book(s)
- Assignments

Text Books:

- "Physical and Engineering Geology", by S.K. Garg, 6th revised edition (2009), Khanna Publishers
- "Structural Geology" by Marland P. Billings, 3rd edition (2003), Prentice-Hall of India

Additional text book may be prescribed if necessary

Syllabus includes:

- Introduction to Geology
- Minerals
- Rocks – Rock Cycle
- Seismic map of Bangladesh
- Faults
- Folds
- Domes and Basins
- Erosional process

Introduction

The Earth

The Earth is a system consisting of four major interacting components:

- **Atmosphere - Air**
- **Biosphere – Life Zone**
- **Hydrosphere - Water**
- **Geosphere – Solid Earth**

THE FOUR SPHERES of the Earth system interact continually, each affecting the others.

System Interactions

Volcanoes (geosphere) erupt, sending ash and gases into the air (atmosphere) and sending lava and ash down onto surrounding forests (biosphere) and human habitations (biosphere).

Geosphere → Atmosphere
Geosphere → Biosphere

System Interactions

Earthquakes (geosphere) can damage buildings which may kill people (biosphere), as well as cause fires which release gases into the air (atmosphere). Earthquakes in the ocean may cause a tsunami (hydrosphere) which can eventually hit land and kill both animals and people (biosphere).

Geosphere → Biosphere
Geosphere → Atmosphere
Geosphere → Hydrosphere

Why is Earth a Dynamic Planet?

The Core
- solid inner
- liquid outer
- density of 10-13 gm/cm³

The Mantle
- surrounds the core
- density of 3.3-5.7gm/cm³
- three distinct zones

The Crust
- oceanic - 3 gm/cm³
- continental - 2.7 gm/cm³

Plate Tectonic Theory explains the interactions of these zones

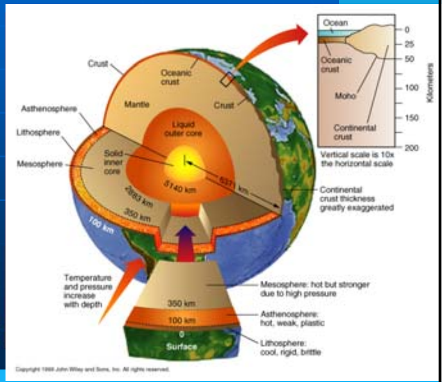
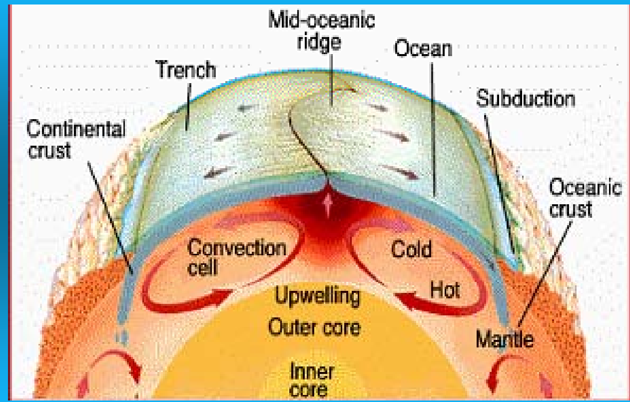
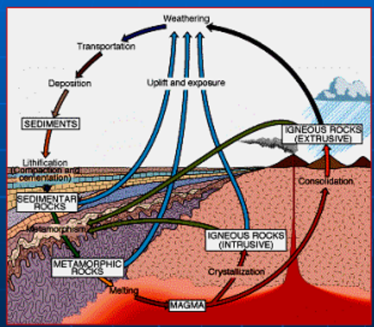


Plate Tectonic Theory



The Rock Cycle



- Provides a way to examine the relationships between internal and external processes
- Relates Igneous, Metamorphic, and Sedimentary rocks to one another and to the processes which 'recycle' earth materials

Geology

Science comprising the study of the dynamics and physical history of the earth, the rocks of which it is composed, and the processes by which the earth's structure changes.

How does the study of Geology benefit us?

An understanding of the dynamic nature of the planet allows us to:

- Appreciate the balance in the delicate systems of nature.
- Make appropriate choices about our interaction with the environment
- Ensure correct decisions regarding natural resource consumption

Applications of Geology

- ❑ **Insights into the history of the Earth**
- ❑ **Primary evidence for plate tectonics**
- ❑ **Mineral and hydrocarbon exploration**
- ❑ **Evaluating water resources**
- ❑ **Prediction and understanding of natural hazards**
- ❑ **Remediation of environmental problems**
- ❑ **Insights into past climate change.**
- ❑ **Role in geotechnical engineering**

Branches of Geology

- ❑ **Minerology**
- ❑ **Physical geology**
- ❑ **Structural geology**
- ❑ **Petrology**
- ❑ **Sedimentology**
- ❑ **Engineering geology – interaction of human activity/infrastructure on earth's crust**
- ❑ **Paleontology**
- ❑ **Geomorphology**

Multi-Disciplinary Areas incorporating Geology

- ❑ **Geophysics**
- ❑ **Seismology**
- ❑ **Geochemistry**

Kathmandu

Geologic Hazard

Adverse geologic condition capable of causing damage or loss of property and life:

- Earthquakes.
- Landslides / Rockfall / Mudflow
- Volcanic Eruption
- Flash Floods
- Forest Fire
- Ground Subsidence / Settlement (Slow event)
- Stream Erosion / Coastal Erosion (Slow event)

Geologic hazards are typically evaluated by engineering geologists who are educated and trained in interpretation of landforms and earth process, earth-structure interaction, and in geologic hazards.

Minerals

MINERAL

The solid crust of the earth is made up of rocks, which in turn are aggregates of minerals. The minerals are therefore the smallest geological units forming the crust and are themselves substances of inorganic nature. Minerals are characterized by more or less fixed chemical compostion and are often found to occur in nature showing perfect geometric forms and characteristic internal atomic structure.

MINERAL (Contd.)

A mineral is a naturally occurring substance with a characteristic internal structure determined by a regular arrangement of atoms or ions within it, and with chemical and physical properties that are either fixed or that vary within certain definite limits.

Minerals are alike physically and chemically no matter where it comes from.

The most definitive characteristic of a mineral is its internal structure.

Crystal

A crystal or crystalline solid is a solid material whose constituent atoms, molecules, or ions are arranged in an ordered pattern extending in all three spatial dimensions. In addition to their microscopic structure, large crystals are usually identifiable by their macroscopic geometrical shape, consisting of flat faces with specific, characteristic orientations.

Examples of large crystals include snowflakes, diamonds, and table salt. Most inorganic solids are not crystals but polycrystals, i.e. many microscopic crystals fused together into a single solid. Examples of polycrystals include most metals, rocks and ice.

Crystal (contd.)

Most minerals are crystalline substances i.e., they have an orderly internal structure. Some minerals show pure crystal forms which are defined as solid forms bounded by smooth planes, manifesting an orderly internal structure. Note the difference between crystalline substance and crystal.

It has been observed that faces of such crystal always meet at characteristic angles, regardless of size and gross shape of crystal. The constancy of the interfacial angles for same mineral indicates that the crystal is built of minute particles packed together in a definite geometric pattern.

Crystal (contd.)

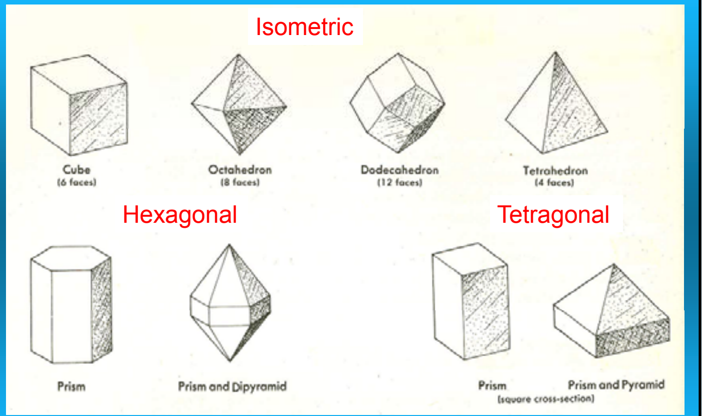
The same mineral composition in some cases can develop more than one crystal structure. For example carbon occurs in nature in two forms:
(i) Graphite – hexagonal crystals, very soft, opaque, specific gravity 2.3
(ii) Diamond – cubic crystals, hardest mineral, transparent, specific gravity 3.5.
Diamonds have been formed by extreme high pressure.

Even though the crystalline nature of mineral may not be obvious in a solid rock, it can usually be confirmed using microscope or always by X-Ray diffraction.

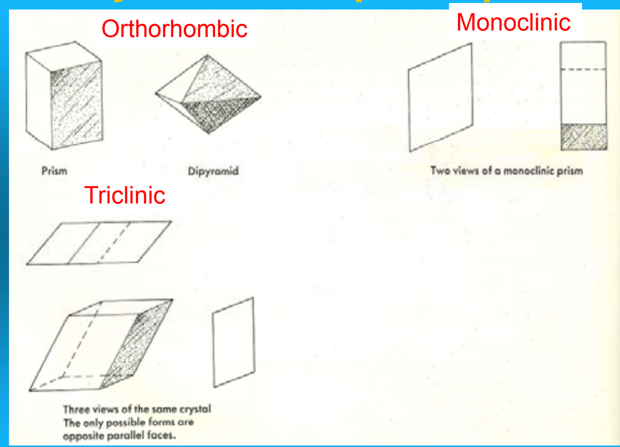
Crystal (contd.)

- All crystalline substances crystallizes in one of six crystal systems.
- If the mineral grows in unrestricted space, it develops the external shape of its form.
- Many external forms are possible in each of the systems; however the system can be determined by the symmetry of the crystal.
- If the mineral cannot grow into its external shape , its crystalline nature can be determined only under the microscope or by X-Ray analysis.
- Crystallography is a fascinating subject.

Crystal Forms



Crystal Forms (contd.)



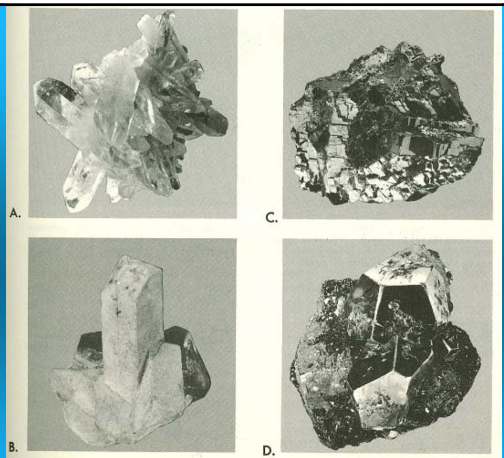
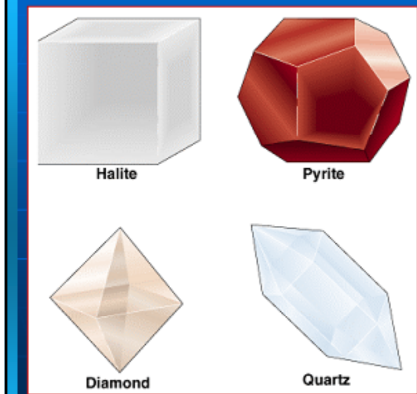


FIG. 2-20. *Mineral specimens showing crystal forms. Parts A. Quartz and C. Galena from Ward's Natural Science Establishment, Inc., Rochester, N. Y., Parts B. Orthoclase (potassium feldspar) and D. Pyrite are from the Smithsonian Institution.*



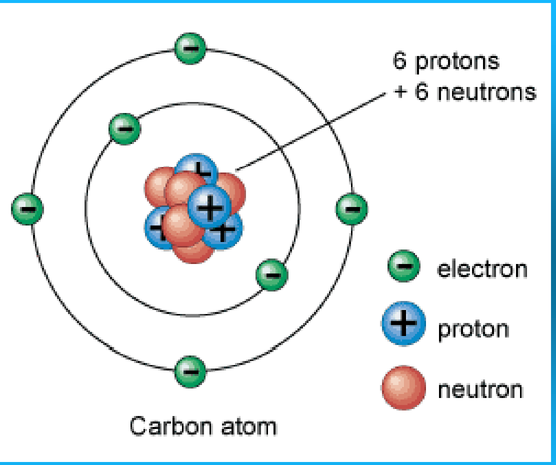
- **Mineral Crystals**
  - **Can occur in a variety of shapes which reflect the orderly internal arrangement of atoms.**

Atomic Theory

- All matter is composed of tiny individual particles called atoms. Atoms may have diameters of a few tenths of a nanometer. Atoms can only be observed individually using scanning tunneling microscope.
- Each atom is composed of three sub-atomic particles namely proton, neutron and electron. Atom consists of a dense central nucleus consisting of positively charged proton and electrically neutral neutron surrounded by a cloud of negatively charged electrons. Over 99.94% of an atom's mass is concentrated in the nucleus, with protons and neutrons having roughly equal mass

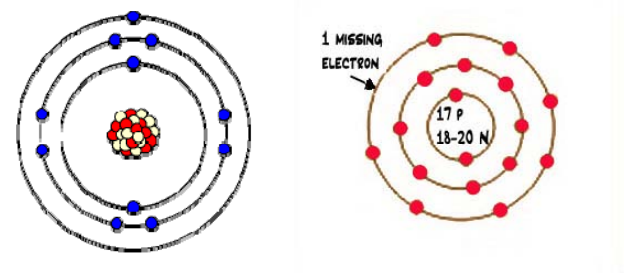
Atomic Theory (contd)

- The chemical characteristics of an element seem to entirely depend on the number of positive electrical charges i.e., number of protons in its nucleus. This number is known as the atomic number of an element.
- Electrons circle about the nucleus in a set of concentric shells. Electrons are attracted to the protons in the nucleus by electromagnetic force. The electron is by far the lightest sub-atomic particle at 9.11×10^{-31} kg, with a size too small to be measured using available techniques.
- Chemical bonds between atoms occur due to the interactions between their constituent electrons



Atomic Theory (contd)

- Atoms are electrically neutral if they have an equal number of protons and electrons. If an atom has more or fewer electrons than its atomic number, then it becomes respectively negatively or positively charged; a charged atom is called **ion**. Ions can be created by both chemical and physical means.
- The outermost electron shell of an atom in its uncombined state is known as the valence shell, and the electrons in that shell are called valence electrons. The number of valence electrons determines the bonding behavior with other atoms. Atoms tend to chemically react with each other in a manner that fills (or empties) their outer valence shells.



Sodium atom

Chlorine atom

"One" electron is transferred from sodium to chlorine, forming sodium cations and chloride anions. Being oppositely charged, these cations and anions form ionic bonds and combine to form sodium chloride, NaCl

Ion Size and Atom size

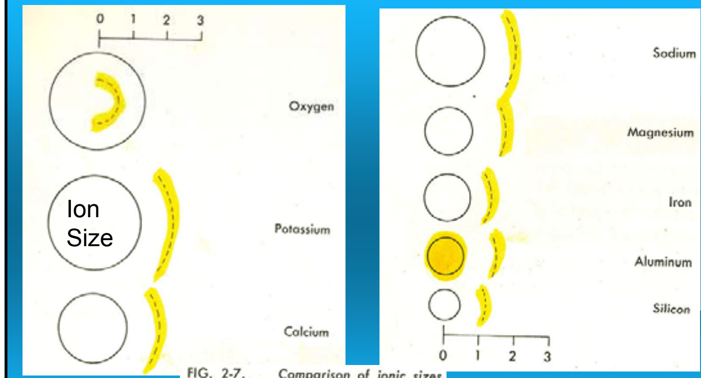
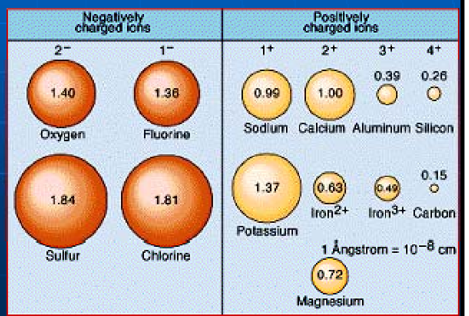


FIG. 2-7. Comparison of ionic sizes of some common elements. Their atomic sizes are indicated by the dashed lines. The scale is angstroms (1 angstrom is one ten-millionth of a millimeter).

Chemical Composition of Minerals

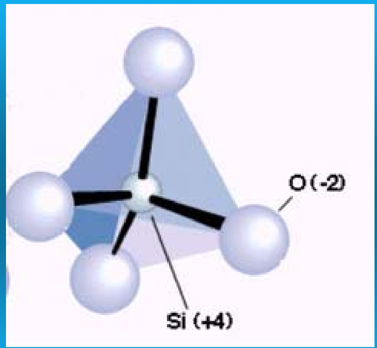
- Shown by a chemical formula such as NaCl or SiO_2 (Halite, Quartz)
- A range of compositions may be indicated as in $(Mg,Fe)_2SiO_4$ (Olivine), where either magnesium, iron, or a combination of both make up the molecular structure



How Many Minerals are Known?

- More than 3,500 identified
  - Less than 25 are common as rock forming minerals
  - They are composed of the most abundant elements found in the crust
- Most abundant elements in the crust (% weight)
  - Oxygen- 46.6
  - Silicon- 27.7
  - Aluminum- 8.1
  - Iron- 5.0
  - Calcium- 3.6
  - Sodium- 2.8
  - Potassium- 2.6
  - Magnesium- 2.1
  - all others- 1.5

Silicon Tetrahedron

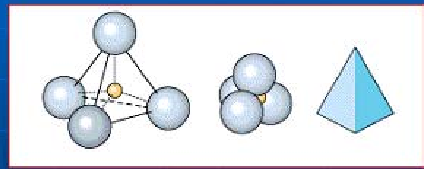


The crust is dominated by the elements oxygen and silicon.

Silicon tetrahedron is a ion (not a molecule) with four negative charges

It can combine with say two ions of Mg++ or Fe++ as in the mineral olivine.

- **The Silicate Minerals**



- **Built from the two most abundant elements in the earth's crust, atoms are arranged in a tetrahedron, with oxygen atoms at the four corners.**
- **The silica tetrahedron is the basic building block for all the silicate minerals.**

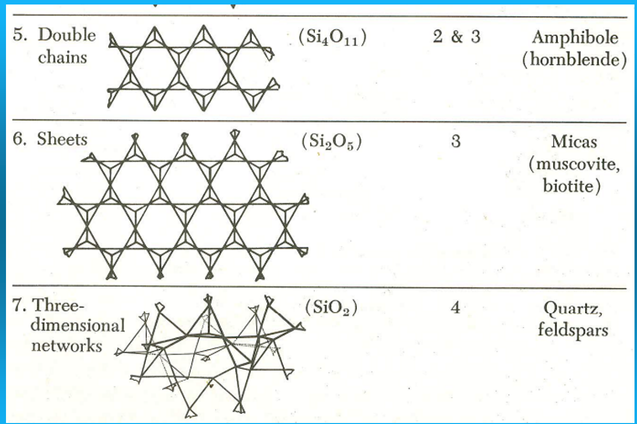
Silicate Minerals

- Minerals that contain silicon tetrahedron (SiO_4) ion are called silicates, these dominate the earth's crust.
- Silicates are formed by combinations of the negatively charged silicon tetrahedron ion with other elements.
- The structures of silicate minerals are determined by the way these silicon tetrahedron are arranged.

Structure of Silicate Minerals

	Formula of silicon-oxygen unit	Number of oxygen shared	Example
1. Single tetrahedron	(SiO_4)	0	Olivine
2. Double tetrahedron	(Si_2O_7)	1	Epidote
3. Ring	(Si_6O_{18})	2	Tourmaline
4. Chains	(SiO_3)	2	Pyroxene (augite)

Structure of Silicate Minerals (Contd.)



5. Double chains	(Si_4O_{11})	2 & 3	Amphibole (hornblende)
6. Sheets	(Si_2O_5)	3	Micas (muscovite, biotite)
7. Three-dimensional networks	(SiO_2)	4	Quartz, feldspars

- Common silicates
  - Quartz, feldspars, muscovite mica
  - Pyroxene, amphibole, biotite mica
- Common non-silicates
  - Calcite, dolomite, gypsum, halite

Physical Properties of Minerals

- **Color and Luster**
  - Color may vary because of impurities or variations in the range of the chemical formula
  - Luster is the appearance of the mineral in reflected light

Color (light vs. dark) and Luster (metallic vs. nonmetallic)

Physical Properties of Minerals (contd.)

- **Crystal Form**
  - External form is a reflection of the internal geometry and composition
  - Perfect crystals are rare, but may be useful in identification

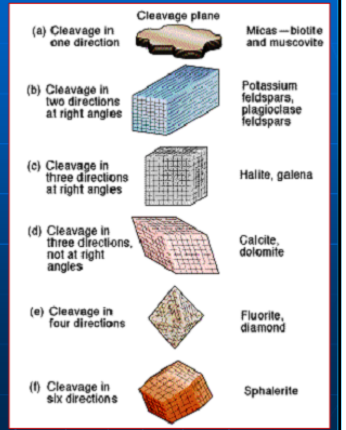
Streak

- When a mineral is rubbed across a piece of porcelain tile a streak of powdered mineral is left behind.

Physical Properties of Minerals (contd.)

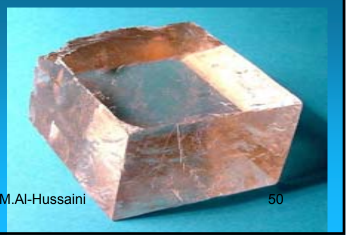
Cleavage and Fracture

- **Cleavage is the tendency of a mineral to break along planes that exist between weak bonds in the internal geometric structure**
- **Fracture is breakage along irregular surfaces when no weak planes exist**



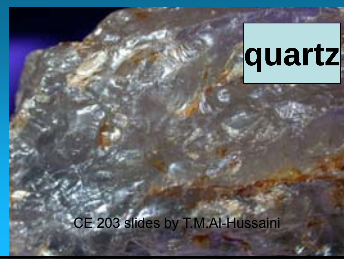
Cleavage

- Cleavage is the way that mineral breaks.
- Minerals that break along smooth, flat surfaces have cleavage.
- Mica has cleavage



and Fracture!...

- Mineral that breaks uneven, rough, or jagged surfaces have fracture.
- Quartz has fracture



Physical Properties of Minerals (contd.)

The planes of weakness that are the cleavage directions in a mineral are caused by the atomic structure of the mineral. Cleavages form along directions of weak bonding as shown in Fig. 2-24.

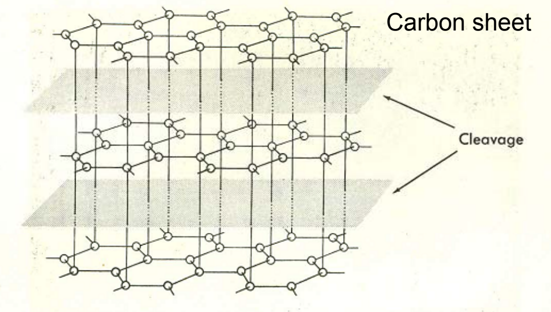


FIG. 2-24. *Structure of graphite. The bonds between the carbon sheets are weak, causing the cleavage in graphite.*

Physical Properties of Minerals (contd.)

Quartz has a hardness of 7 and shows conchoidal fracture

- **Hardness**
  - The resistance of a mineral to abrasion
  - Determined by internal structure and strength of bonds
  - Based on the Mohs scale from 1 to 10
  - An important lab test in the identification of minerals

Physical Properties of Minerals (contd.)

In 1812, Mohs arranged ten minerals in order of hardness, so each will scratch those lower in the scale. This is still used today. It is not a regular scale. There is a far greater gap between diamond and corundum, than between any other two. But it is a useful way to measure the property of hardness.

Physical Properties of Minerals (contd.)

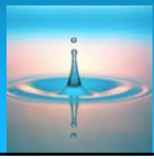
Mohs Hardness Scale

Mineral	Rating	Testing Method
Talc	1	Softest known mineral. It flakes easily when scratched by a fingernail.
Gypsum	2	A fingernail can easily scratch it.
Calcite	3	A fingernail cannot scratch it, but a copper penny can.
Fluorite	4	A steel knife can easily scratch it.
Apatite	5	A steel knife can scratch it.
Feldspar	6	Cannot be scratched by a steel knife, but it can scratch window glass.
Quartz	7	Can scratch steel and hard glass easily.
Topaz	8	Can scratch quartz.
Corundum	9	Can scratch topaz.
Diamond	10	Hardest known mineral. Diamond can scratch all other substances.

Specific Gravity

- The specific gravity of a mineral is the ration of its weight **compared** with the weight of an equal volume of water.
- Gold has specific gravity of **19**
- It means gold is **19 times heavier** than water.

19 times heavier



Physical Properties of Minerals (contd.)

Other Useful Mineral Properties

- Taste
- Feel
- Magnetism
- Electrical Conductivity
- Double refraction
- Reaction with simple chemicals such as dilute hydrochloric acid

Mineral Identification:

TABLE 2-8. *Mineral identification key.*

Metallic luster	Black; strongly magnetic; hardness, 6.	MAGNETITE
	Lead-pencil black; smudges fingers; hardness, 1; one cleavage that is apparent only in large crystals.	GRAPHITE
	Brass yellow; black streak; cubic crystals, commonly with striations; hardness, 6-6.5.	PYRITE
	Brass yellow; may be tarnished; black streak; hardness, 3.5-4; massive.	CHALCO-PYRITE
	Shiny gray; black streak; very heavy; cubic cleavage; hardness, 2.5.	GALENA

Mineral Identification (contd.):

Light-colored nonmetallic luster	Hard—not scratched by knife	Shows cleavage	White or flesh-colored; 2 cleavage planes at nearly right angles; hardness, 6. Large crystals which show irregular veining are PERTHITE. $KAlSi_3O_8$	ORTHOCLASE (POTASSIUM FELDSPAR)
			White or green-gray; 2 cleavage planes at nearly right angles; hardness, 6; striations on one cleavage.	PLAGIOCLASE $CaAl_2Si_2O_8$
		No cleavage	White, clear, or any color; glassy luster; transparent to translucent; hexagonal (6-sided) crystals; hardness, 7; conchoidal fracture.	*Quartz* (SiO_2)
			Various shades of green and yellow; glassy luster; granular masses and crystals in rocks; hardness, 6.5-7 (apparent hardness may be much less).	OLIVINE $(Mg,Fe)_2SiO_4$
			Any color or variegated; glassy luster; hardness, 5-6; conchoidal fracture.	OPAL
			Any color or variegated; waxy luster; hardness, 7; conchoidal fracture.	CHALCEDONY (AGATE)
	Soft—scratched by knife	Shows cleavage	Colorless to white; salty taste; cubic cleavage; hardness, 2.5.	HALITE
			White, yellow to colorless; rhombohedral cleavage; hardness, 3; effervesces with dilute hydrochloric acid.	CALCITE
			Pink, colorless, white, or dark; rhombohedral cleavage; hardness, 3.5-4; effervesces with dilute hydrochloric acid only if powdered.	DOLOMITE
			White to transparent; 3 unequal cleavages; hardness, 2.	GYPSUM
			Green to white; feels soapy; 1 cleavage; hardness, 1.	TALC
			Colorless to light yellow or green; transparent in thin sheets which are very elastic; 1 cleavage; hardness, 2-2.5 (white mica).	MUSCOVITE $KAl_2(AlSi_3O_{10})(OH)_2$
			Green to white; fibrous cleavage; may form veins.	ASBESTOS
		No cleavage	Green to white; feels soapy; hardness, 1.	TALC
			White to transparent; hardness, 2.	GYPSUM
			Yellow to greenish; resinous luster; hardness, 1.5-2.5.	SULFUR

Geological Time

We are talking about millions of years

Rates of Geologic Events

Uplift of Alps (Mountain)
- 5 km/10 mil.yr. = 1 cm/20 yr.

Cutting of Grand Canyon
- 2 km/3 mil.yr. = 1 cm/15 yr

Opening of Atlantic Ocean
- 5000 km/180 mil.yr. = 2.8 cm/yr.

Geological Time Scale (contd)

Era	Period	Epoch	Time of start (millions of years ago)
Cenozoic	Quaternary	Holocene	0.1
		Pleistocene	2
	Tertiary	Pliocene	5
		Miocene	24
		Oligocene	37
		Eocene	58
		Paleocene	66
Mesozoic	Cretaceous		144
	Jurassic		208
	Triassic		245
Paleozoic	Permian		286
	Carboniferous:		
	Pennsylvanian		320
	Mississippian		360
	Devonian		408
	Silurian		438
	Ordovician		505
	Cambrian		534
Precambrian			4,600

Geological Time Scale

Era: Geological Time divided into four eras

- **Cenezoic**
  - Time of recent life
  - Fossils resemble modern day living organisms
- **Mesazoic**
  - Time of middle life.
  - Some fossils resemble modern day living organisms
  - Some are different from any living organism on the Earth today.

Geological Time Scale (contd)

- **Paleozoic**
  - Time of ancient life.
  - Fossils are different from anything found on the Earth today.
- **Precambrian**
  - Time before the time of ancient life.
  - Very few fossils are found in this time period

Period

- Eras are further divided into Periods

Epoch

- Periods are further divided into Epochs

Pre-Cambrian Era

- Began with the formation of the Earth 4.6 billion years ago.
- Bacteria appeared 3.5 billion years ago, followed by algae and fungi.

Paleozoic Era

Divided into 6 periods:

Cambrian period - Sponges, snails, clams and worms evolve

Ordovician period - First fishes evolved and other species become extinct

Silurian period - Land plants, insects and spiders appear

Devonian period - Amphibians evolve and cone-bearing plants start to appear.

Carboniferous period - Tropical forests appear and reptiles evolve.

Permian period - Seed plants become common and insects and reptiles become widespread. Sea animals and some amphibians begin to disappear.

Mesozoic Era

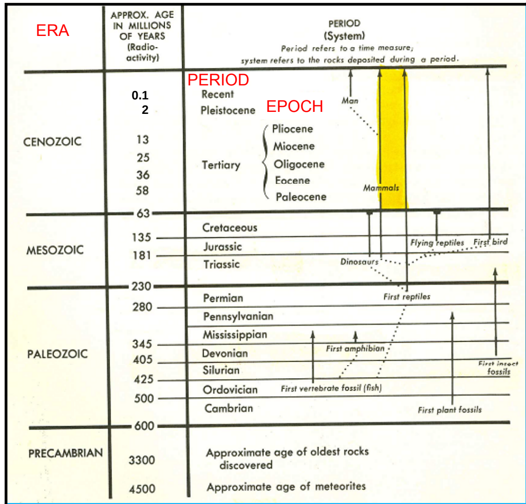
Divided into 3 periods:

- **Triassic period** - Turtles and crocodiles evolve and dinosaurs appear.
- **Jurassic period** - Large dinosaurs roam the world. First mammals and birds appear.
- **Cretaceous period** - Flowering plants appear, mammals become more common, dinosaurs become extinct.

Cenozoic Era

Divided into 2 periods:

- **Tertiary period - First primates appear and flowering plants become the most common.**
- **Quaternary period - Humans evolve and large mammals like woolly mammoths become extinct.**



Geological Time Scale

- Geologic time extends back almost 5 billion years to when the earth was formed
- Geological studies have shown how constant changes, both biological and physical, has been occurring on the earth.

Foster (1969)

Principles of Geological Formation

Principle of uniformity

- Present is the key to the past.
- Geological features of today's Earth has been shaped by its past.
- Processes that are going on today to shape the Earth are the same processes that have always been going on.

Fossils

Fossils are defined as Remains of Ancient Animals and Plants, Evidence of Life

Commonly Preserved Hard Parts of Organisms:

- Bones
- Shells
- Hard Parts of Insects
- Woody Material

Where Fossils Occur

Almost Exclusively in Sedimentary Rocks

- Heat of Melting or Metamorphism Would Destroy Almost Every Type of Fossil
- Rare Exceptions:
  - Some Fossils in Low-grade Metamorphic Rocks
  - Trees Buried by Lava Flow

To Be Preserved, Organisms Have to Be:

- Buried Rapidly After Death
- Preserved From Decay

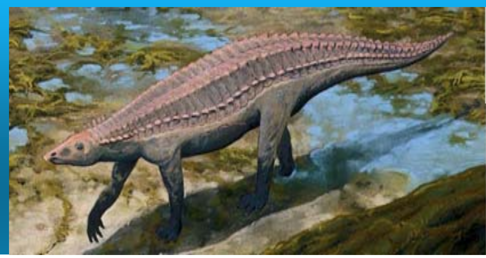
Types of Fossils

PETRIFIED

MOLD

CAST

AETOSAUR FOUND IN THE NATIONAL PETRIFIED FOREST

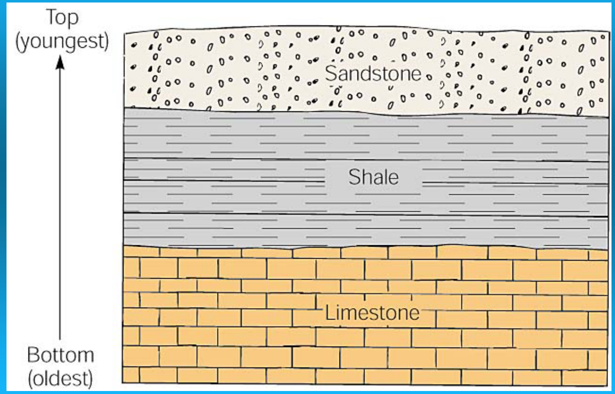


Sometimes whole animals become preserved intact, but this is very rare. If an organism is surrounded by ice or tar they might be discovered looking much the same as they did when they died.

Dating

- **Uses radioactive elements near the fossils to determine the actual age of the fossils.**
- **By determining the age of the radioactive element, scientists can calculate the age of the fossil buried nearby.**
- **The absolute age of fossils is estimated by dating associated igneous rock and lava flows**

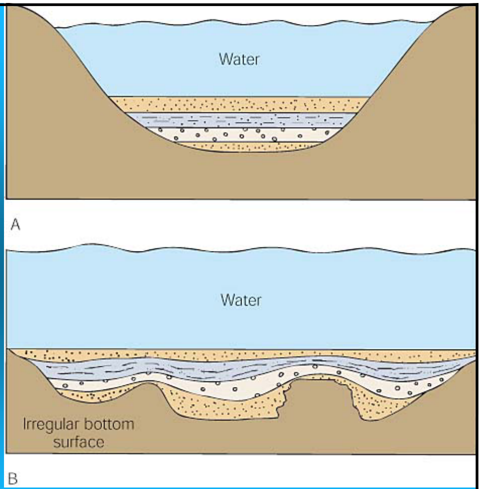
The principle of superposition: In an undisturbed sedimentary sequence, the rocks on the bottom were deposited first, and the depositional ages decrease as you progress to the top of the pile.



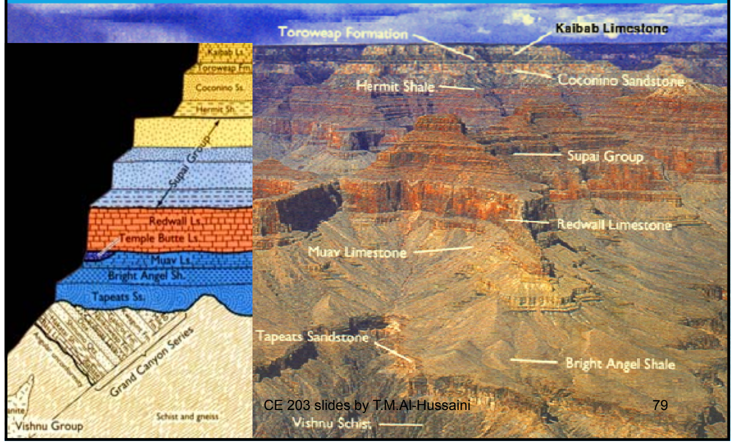
The principle of original horizontality.

(A)Sediments tend to be deposited in horizontal layers.

(B) Even where the sediments are draped over an irregular surface, they tend toward the horizontal.



Grand Canyon, Arizona, USA provides a majestic cross section of horizontal sedimentary rocks. As you go deeper, you encounter older rocks.

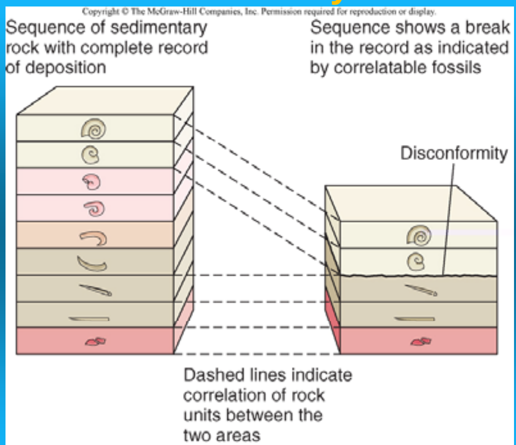


Horizontal Stratification in Grand Canyon

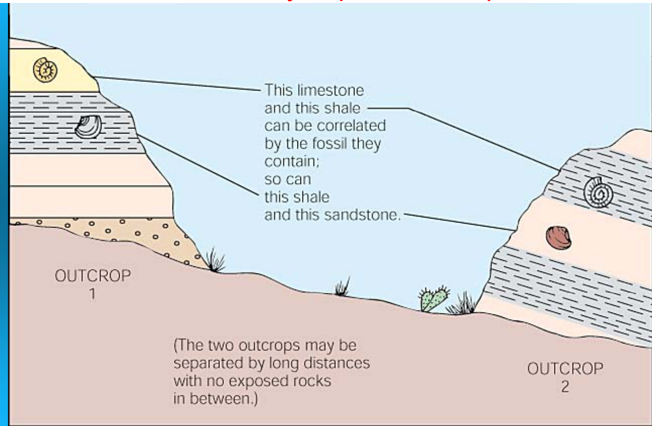
Principle of Lateral Continuity

Sediment layers extend laterally in all direction until they thin & pinch out as they meet the edge of the depositional basin.

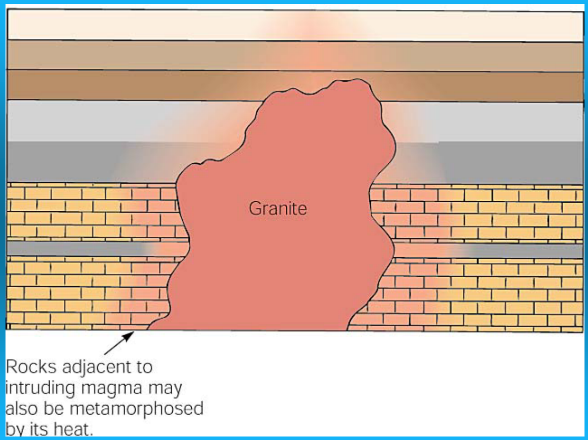
Disconformity



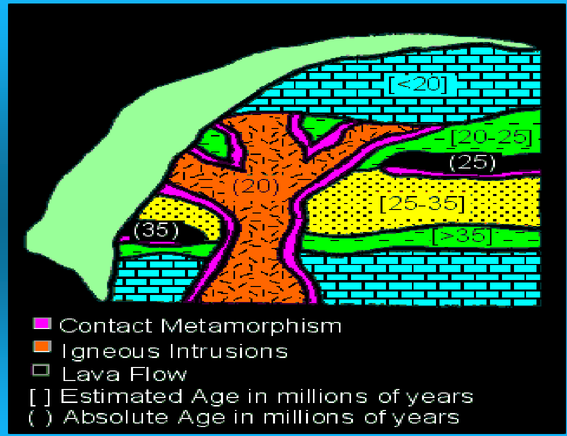
Similarity of fossils suggests similarity of ages, even in different rocks widely separated in space.



A granite intrusion cutting across older rocks.



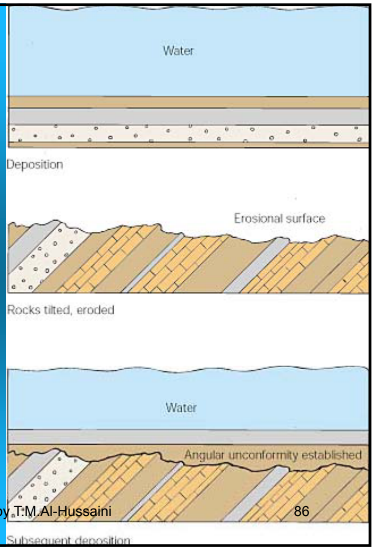
Igneous Intrusion & Contact Metamorphism



Angular unconformity

Development involved sedimentation, tilting or folding and erosion

before sedimentation is resumed.

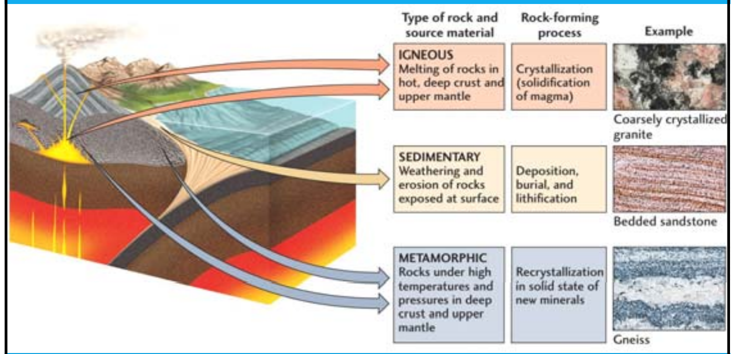


This **dinosaur footprint** is in shale near Tuba City, Arizona. It tells you something about the relative age of the shale, since it must have been soft mud when the dinosaur stepped here.

Rocks

Rock is a naturally occurring solid aggregate of one or more minerals that have been cohesively bound together by a natural process. Examples are marble, granite, sandstone, limestone, etc.

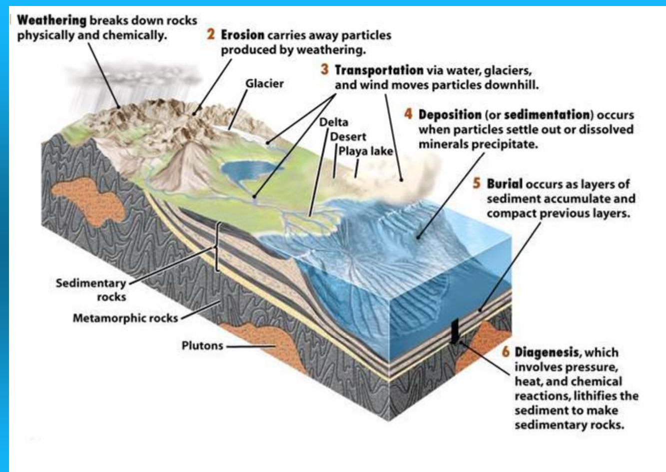
Three Types of Rocks



Common Minerals Found in Rocks

Igneous Rocks	Sedimentary Rocks	Metamorphic Rocks
Quartz*	Quartz*	Quartz*
Feldspar*	Clay minerals*	Feldspar*
Mica*	Feldspar*	Mica*
Pyroxene*	Calcite	Garnet*
Amphibole*	Dolomite	Pyroxene*
Olivine*	Gypsum	Staurolite*
	Halite	Kyanite*

An asterisk indicates that a mineral is a silicate.

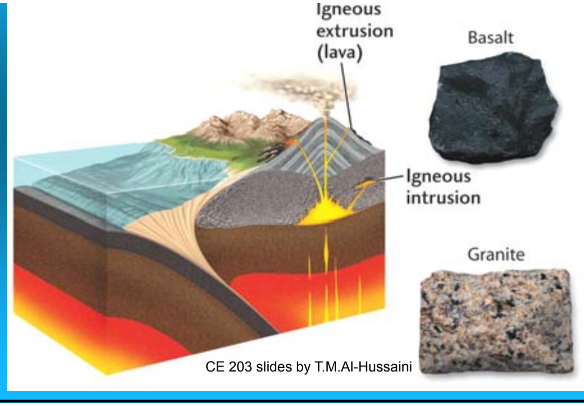


Igneous Rocks

Igneous rocks are formed by solidification of a melt known as magma. Magma is a natural hot melt composed of a solution of rock-forming materials. Magma originates near the bottom of the crust.

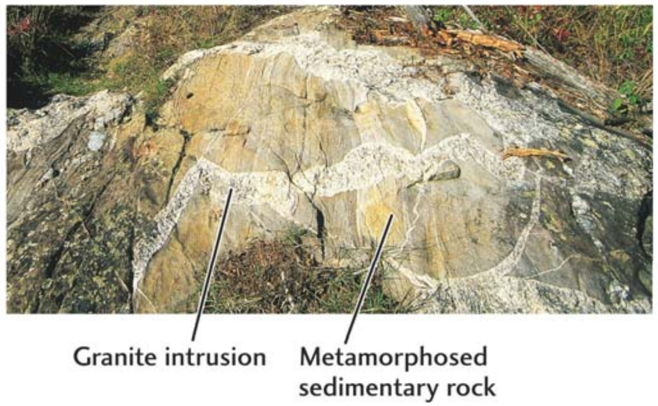
Two Types of Igneous Rocks

Extrusive igneous rocks form when magma erupts at the surface (i.e., above ground) and rapidly cools.
Intrusive igneous rocks form when magma intrudes into bedrock and slowly cools (i.e., below ground)



Intrusive Igneous Rocks (exposed)

Intrusive igneous rocks crystallized from slowly cooling magma intruded within the Earth's crust, such as granite and gabbro



Intrusive Igneous Rocks

Specimens about two inch in width (www.geology.com)

Gabbro is a coarse-grained, dark colored, intrusive igneous rock that contains feldspar, augite and sometimes olivine. Most abundant rock in deep oceanic crust.

Granite is a coarse-grained, light colored, intrusive igneous rock that contains mainly quartz and feldspar minerals

Diorite is a coarse-grained, intrusive igneous rock that contains a mixture of feldspar, pyroxine, hornblende and little quartz. Intermediate in composition between Granite and Gabbro.

Extrusive Igneous Rocks

Extrusive igneous rocks formed from the cooling of lavas extruded onto the Earth's surface or onto ocean floors

Rocks formed by the cooling of pyroclastic material, such as fragmented pieces of magma and material erupted into the air

Extrusive Igneous Rocks

Specimens about two inch in width (www.geology.com)

Rapid cooling of lava at earth's surface, generally does not allow mineral crystals to grow large enough to be seen with the unaided eye, so extrusive rocks are usually fine-grained

Basalt is a fine-grained, dark-colored extrusive igneous rock composed mainly of plagioclase and pyroxene minerals. It is Earth's most abundant bedrock. Composition similar to Gabbro.

Andesite is a fine-grained, extrusive igneous rock composed mainly of plagioclase with other minerals such as hornblende, pyroxene and biotite. Similar in Composition with Diorite.

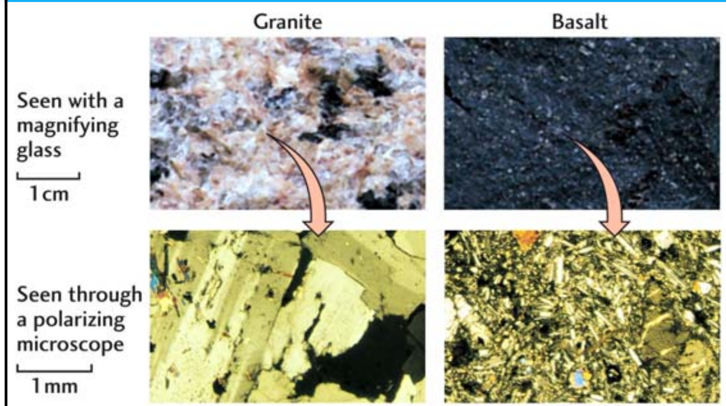
Pumice is a light-colored, extremely porous igneous rock that forms during explosive volcanic eruptions. The vesicular texture is a result of gas trapped in the melt at the time of solidification.

Igneous Rock Texture

Intrusive rocks such as granite are coarse grained (can easily see the grains with the unaided eye).

Extrusive igneous rocks such as basalt are glassy or fine grained.

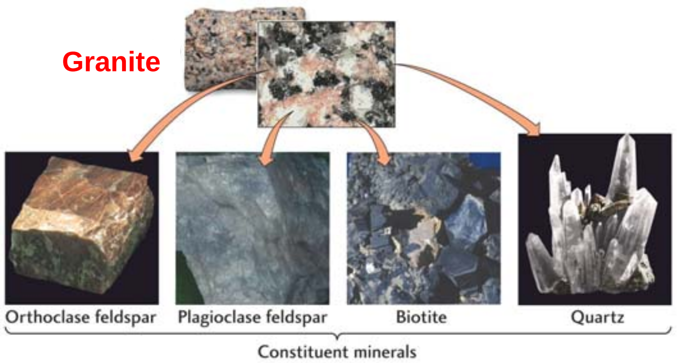
Igneous Rock Texture (contd.)



Constituent Minerals of Igneous Rocks

Most Igneous Rocks are Silicates:

Quartz, Feldspar, Mica, Pyroxene, Amphibole, Olivine



Common Minerals of Igneous Rocks

Compositional Group	Mineral	Chemical Composition	Silicate Structure
	Quartz	SiO_2	Frameworks
	Potassium feldspar	$KAlSi_3O_8$	
FELSIC	Plagioclase feldspar	$\{NaAlSi_3O_8$, $CaAl_2Si_2O_8$	
	Muscovite (mica)	$KAl_3Si_3O_{10}(OH)_2$	Sheets
	Biotite (mica)	K, Mg, Fe, Al } $Si_3O_{10}(OH)_2$	
	Amphibole group	Mg, Fe, Ca, Na } $Si8O_{22}(OH)_2$	Double chains
MAFIC	Pyroxene group	Mg, Fe, Ca, Al } SiO_3	Single chains
	Olivine	$(Mg,Fe)_2SiO_4$	Isolated tetrahedra

Types of Igneous Rocks based on Mineralogy

- Felsic
- Intermediate
- Mafic
- Ultramafic

Felsic Igneous Rocks

Rich (high) in minerals containing silica

Poor (low) in iron and magnesium

They include: Granite (Intrusive)
Rhyolite

Mafic Igneous Rocks

Poor (low) in minerals containing silica

Rich (high) in iron and magnesium

They include: Gabbro (Intrusive)
Basalt (Extrusive)

Intermediate Igneous Rocks

Intermediate in composition between felsic and mafic igneous rocks

Less silica, more Fe & Mg than felsic

More silica, less Fe & Mg than mafic

They include: Granodiorite
Dacite
Diorite
Andesite

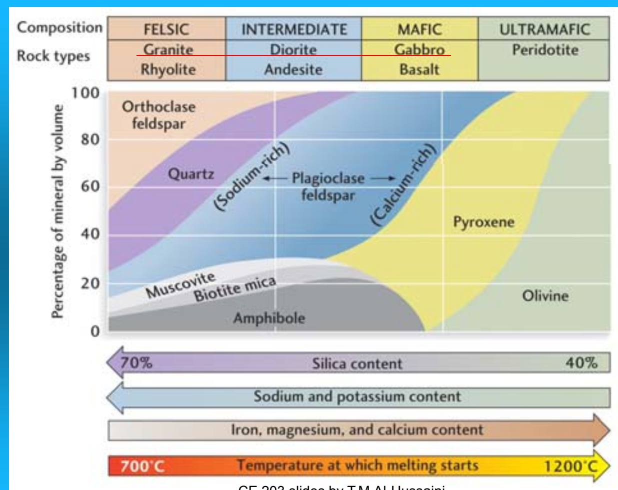
Ultramafic Igneous Rocks

Very uncommon on the Earth's surface

Very poor (lower) in minerals containing silica

Consist primarily of mafic minerals (olivine, pyroxene)

The most common ultramafic rock is: Peridotite



	Felsic	Intermediate		Mafic
Coarse-Grained (intrusive)	Granite	Granodiorite	Diorite	Gabbro
Fine-Grained (extrusive)	Rhyolite	Dacite	Andesite	Basalt

← Silica increasing

← Sodium increasing

← Potassium increasing

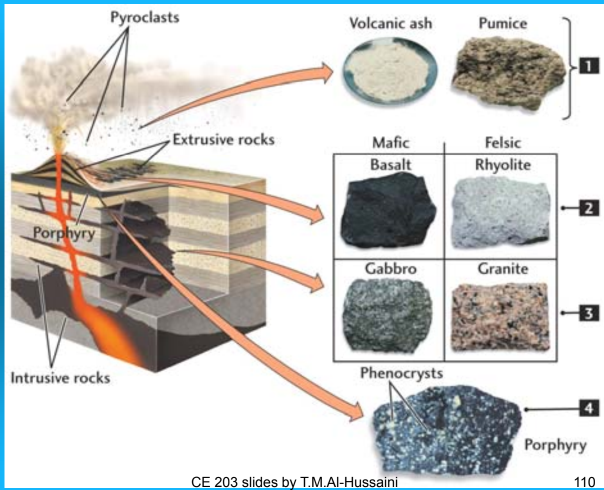
Calcium increasing →

Magnesium increasing →

Iron increasing →

← (Viscosity increasing)

(Melting temperature increasing) →



When Do Rocks Melt?

Melting starts at ~700º C

When the temperature exceeds the melting point of the rock or some minerals within the rock

Composition: Different Minerals melt at different temperatures. Felsic minerals melt at lower temperatures than mafic minerals

Pressure: Increased pressures raises melting points

Water Content: Increased water content lowers melting points

Magma Differentiation

Occurs because different minerals crystallize (solidify) at different temperatures.

In other words, as the magma cools some minerals form first, some form last.

Fractional Crystallization

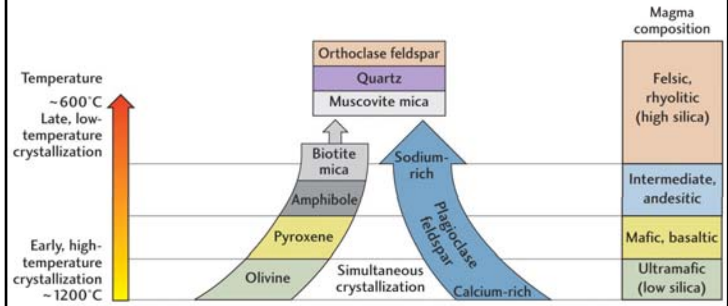
The elements (such as Fe and Mg) used to create the newly formed crystals are now no longer available for creating new minerals

Therefore the chemical composition of the magma slowly changes as new minerals are continually formed and the available matter is selectively used up

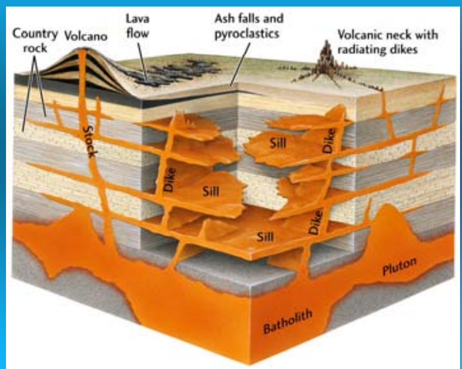
Bowen's Reaction Series

Bowen's Reaction series shows the sequence in which minerals crystallize from a cooling magma.

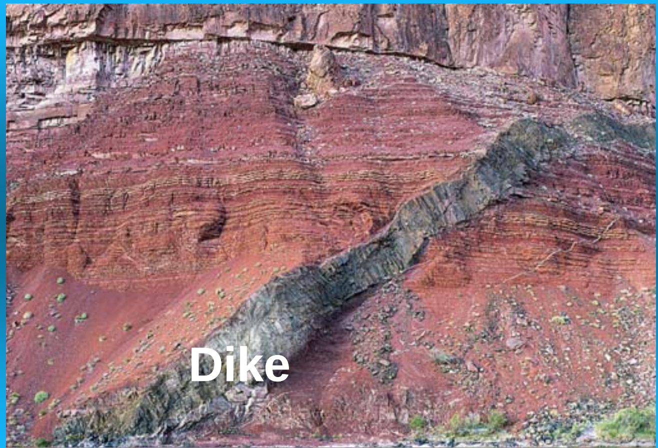
Conducted by Norman L. Bowen prior to 1916



Types of intrusive and extrusive igneous structures

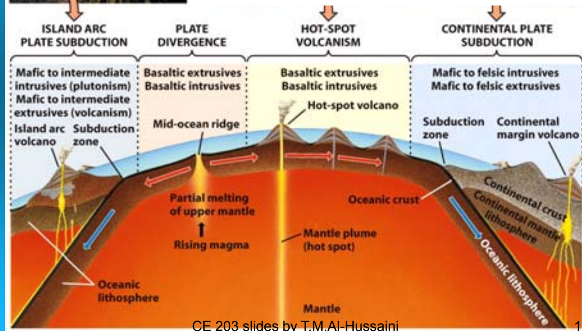


If an intrusive igneous rock does not cut across the surrounding rock's bedding, then it is known as a concordant intrusion, or a sill.



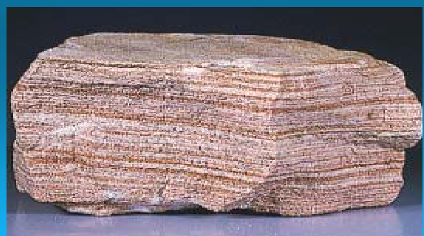
Where Do Most Magmas Occur?

Divergent Plate Margins
Convergent Plate Margins
Mantle Plumes/Hot Spots



Sedimentary Rocks

Rocks formed by deposition and consolidation of new sediments in layers over pre-existing rocks



Extent of Sedimentary Rocks

Only 5% of volume of the Earth's crust

Covering 75 % of exposed surface area of continents

Features of Sedimentary Rocks

Sedimentary rocks may exhibit extensive horizontal layers called bedding.

Sedimentary rocks often contain fossils. Fossils in sedimentary rocks give clues to the history of life

Important resources (coal, oil) are found in sedimentary rocks

Sediments

- *Sediment* - loose, solid particles originating from:
  - Weathering and erosion of pre-existing rocks
  - Chemical precipitation from solution, including secretion by organisms in water
- Classified by particle size
  - Boulder - >256 mm
  - Cobble - 64 to 256 mm
  - Pebble - 2 to 64 mm
  - Sand - 1/16 to 2 mm
  - Silt - 1/256 to 1/16 mm
  - Clay - <1/256 mm

Types of Sediments

- **Clastic sediments are physically deposited particles derived from weathered rocks**
- **Chemical and biochemical sediments include minerals carried in solution such as calcite and halite**

Lithification

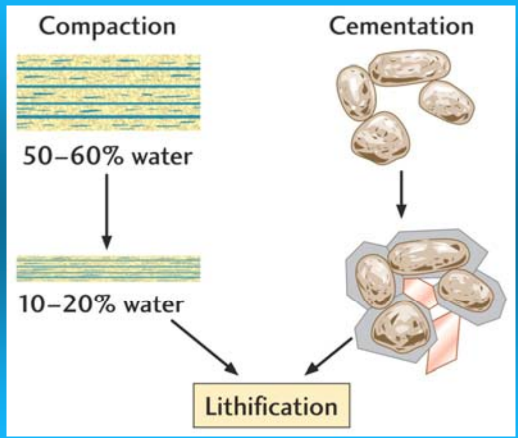
Lithification includes all the processes which convert unconsolidated sediments into sedimentary rocks.

Lithification includes compaction and cementation.

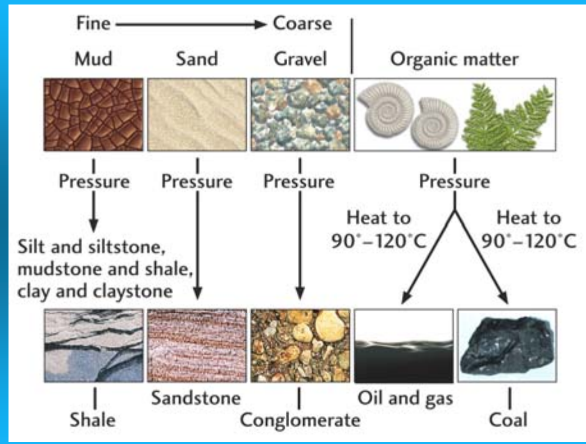
The sediment may be compacted by rearrangement of grains by weight of overlying sediments, reducing pore space and driving out interstitial liquid.

Cementation occurs through the precipitation of binding material around sediments. Binding material may include any chemically precipitated material, such as carbonate, gypsum, and barite.

Lithification (contd.)



Transformation of Sediments



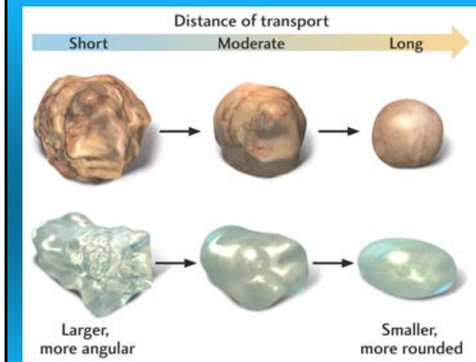
Transportation of Sediments

Movement of sediment away from its source, typically by water, wind, or ice (glacier).

Rounding of particles occurs due to abrasion during transport.

Sorting occurs as sediment is separated according to grain size by transport agents, especially running water. Sediment size decreases with increased transport distance

Roundness of Particles



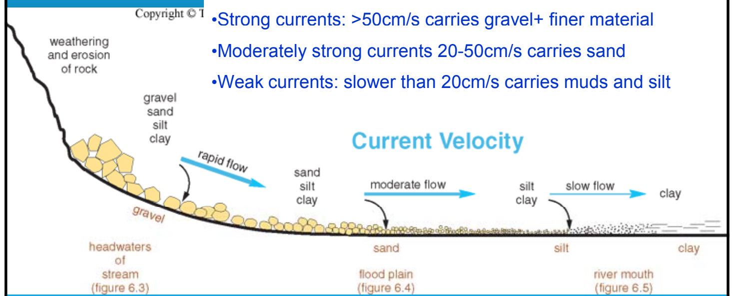
Roundness: measure of how rounded the corners are

- Angular grains close to its source
- Rounded grains transported for a great distance

Transportation of Sediments by Water
Sorting of Particles

Most sediments are carried by rivers: 25 billion tons/year

- •Strong currents: >50cm/s carries gravel+ finer material
- •Moderately strong currents 20-50cm/s carries sand
- •Weak currents: slower than 20cm/s carries muds and silt



Types of Sedimentary Rocks

- *Clastic sedimentary rocks*
  – Most common sedimentary rock type
  – Form from cemented sediment grains that come from pre-existing rocks
- *Chemical sedimentary rocks*
  – Have distinct crystalline textures
  – Form by precipitation of minerals from solution
- *Organic (Biochemical) sedimentary rocks*
  – Accumulate from remains of organisms

Classification of Clastic Sediments based on Particle Size

Table 8.3 Major Classes of Clastic Sediments and Sedimentary Rocks

Particle Size	Sediment	Rock
COARSE	GRAVEL	
Larger than 256 mm	Boulder	Conglomerate
256–64 mm	Cobble	Conglomerate
64–2 mm	Pebble	Conglomerate
MEDIUM		
2–0.062 mm	SAND	Sandstone
FINE	MUD	
0.062–0.0039 mm	Silt	Siltstone
Finer than 0.0039 mm	Clay	Mudstone (blocky fracture) Shale (breaks along bedding) Claystone

Clastic Sedimentary Rocks

- *Breccia and Conglomerate*
  – *Coarse-grained clastic* sedimentary rocks
  – Sedimentary breccia composed of coarse, *angular rock fragments* cemented together
  – Conglomerate composed of *rounded gravel* cemented together
- *Sandstone*
  – *Medium-grained clastic* sedimentary rock
  – Types determined by composition
    - *Quartz sandstone* - >90% quartz grains
    - *Arkose* - mostly feldspar and quartz grains
    - *Graywacke* - sand grains surrounded by dark, fine-grained matrix, often clay-rich

Clastic Sedimentary Rocks

- *Shale*
  - Fine-grained clastic sedimentary rock
  - Splits into thin layers (*fissile*)
  - Silt- and clay-sized grains
  - Sediment deposited in lake bottoms, river deltas, floodplains, and on deep ocean floor
- *Siltstone*
  - Slightly coarser-grained than shales
  - Lacks fissility
- *Claystone*
  - Predominantly clay-sized grains; non-fissile
- *Mudstone*
  - Silt- and clay-sized grains; massive/blocky

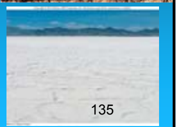
Classification of Biochemical and Chemical Sediments

Table 8.4 Classification of Biochemical and Chemical Sediments and Sedimentary Rocks

Sediment	Rock	Chemical Composition	Minerals
BIOCHEMICAL			
Sand and mud (primarily bioclastic)	Limestone	Calcium carbonate ($CaCO_3$)	Calcite (aragonite)
Siliceous sediment	Chert	Silica (SiO_2)	Opal, chalcedony, quartz
Peat, organic matter	Organics	Carbon compounds Carbon compounded with oxygen and hydrogen	(coal), (oil), (gas)
CHEMICAL			
No primary sediment (formed by diagenesis)	Dolostone	Calcium-magnesium carbonate ($CaMg[CO_3]_2$)	Dolomite
Iron oxide sediment	Iron formation	Iron silicate; oxide (Fe_2O_3); carbonate	Hematite, limonite, siderite
Evaporite sediment	Evaporite	Sodium chloride ($NaCl$); calcium sulfate ($CaSO_4$)	Gypsum, anhydrite, halite, other salts
No primary sediment (formed by diagenesis)	Phosphorite	Calcium phosphate ($Ca_3[PO_4]_2$)	Apatite

Chemical Sedimentary Rocks

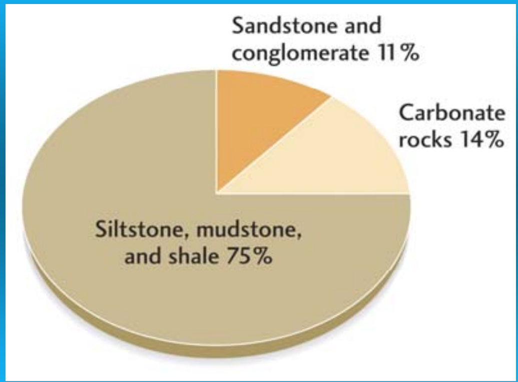
- *Carbonates*
  - Contain CO_3 as part of their chemical composition
  - *Limestone* is composed mainly of *calcite*
    - Most are *biochemical*, but can be *inorganic*
    - Often contain easily recognizable fossils
    - Chemical alteration of limestone in Mg-rich water solutions can produce *dolomite*
- *Chert*
  - Hard, compact, fine-grained, formed almost entirely of silica
  - Can occur as layers or as lumpy nodules within other sedimentary rocks, especially limestones
- *Evaporites*
  - Form from evaporating saline waters (lake, ocean)
  - Common examples are rock gypsum, rock salt



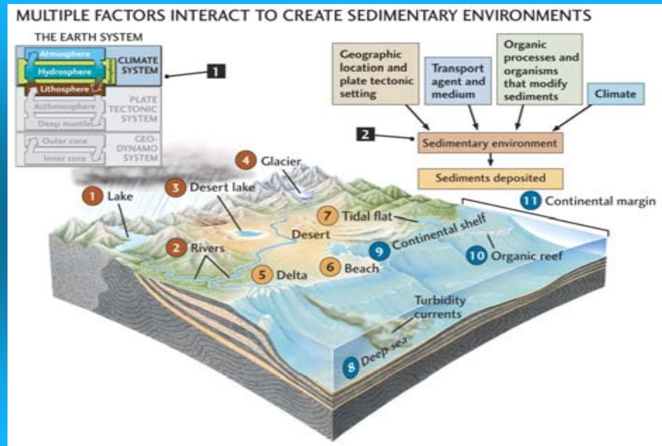
Organics in Sedimentary Rocks

- *Coal*
  - Sedimentary rock forming from compaction of partially decayed plant material
  - Organic material deposited in water with low oxygen content (i.e., stagnant)
- *Oil and natural gas*
  - Originate from organic matter in marine sediment
  - Subsurface "cooking" can change organic solids to oil and natural gas
  - Can accumulate in porous overlying rocks

Distribution of Sedimentary Rocks



Sedimentary environments



Clastic Sedimentary environment

3 Continental Environments

	1 Lake	2 Alluvial	3 Desert	4 Glacial
Transport agent	Lake currents, waves	River currents	Wind	Ice, meltwater
Sediments	Sand and mud, saline precipitates in arid climates	Sand, mud, and gravel	Sand and dust	Sand, mud, and gravel
Climate	Arid to humid	Arid to humid	Arid	Cold
Organic processes	Freshwater organisms and precipitates	Organic matter in muddy flood deposits	Little organic activity	Little organic activity

4 Shoreline Environments

Dominated by actions of waves, tides and currents

	5 Delta	6 Beach	7 Tidal flats
Transport agent	River currents, waves	Waves, tidal currents	Tidal currents
Sediments	Sand and mud	Sand and gravel	Sand and mud
Climate	Arid to humid	Arid to humid	Arid to humid
Organic processes	Burial of plant debris	Little organic activity	Organisms mix sediments

5 Marine Environments

Primary influenced by currents

	8 Deep sea	9 Continental shelf	10 Organic reefs	11 Continental margin
Transport agent	Ocean currents Turbidity currents	Waves and tides	Waves and tides	Ocean currents and waves
Sediments	Mud and sand	Sand and mud	Calcified organisms	Mud and sand
Organic processes	Deposition of remains of organisms	Deposition of remains of organisms	Secretion of carbonates by corals and other organisms	Deposition of remains of organsims

Sedimentary Structures

- Sedimentary structures are features observed in sedimentary rocks which form during or shortly after deposition of the sediment, but before lithification.
- Some sedimentary structures are created by the water or wind which moves the sediment. Other sedimentary structures form after deposition — such as footprints, worm trails, or mudcracks.
- Sedimentary structures can provide information about the environmental conditions under which the sediment was deposited; some structures form in quiet water under low energy conditions, whereas others form in moving water or high energy conditions.

Sedimentary Structures (contd.)

- **Bedding**
- **Cross-Bedding**
- **Graded Bedding**
- **Ripple Marks**
- **Mud-Cracks**
- **Scour Marks**
- **Fossils**

Bedding

- Most common sedimentary structure
- The layers (or beds or strata) are visible because of differences in the color or texture of adjacent beds.
- Strata thicker than 1 cm are commonly referred to as beds. Thinner layers are called laminations or laminae. The upper and lower surfaces of these layers are called bedding planes.

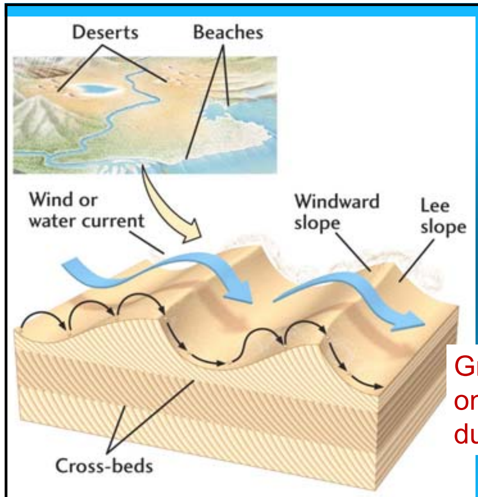
Cross-Bedding

❖Original depositional layering is tilted, and the tilting is not a result of post-depositional deformation.

❖Occurs only in granular sediments. Common in sandstones.

❖Cross bedding forms during deposition on the inclined surfaces of bedforms such as ripples and dunes, and indicates that the depositional environment contained a flowing medium (typically water or wind).

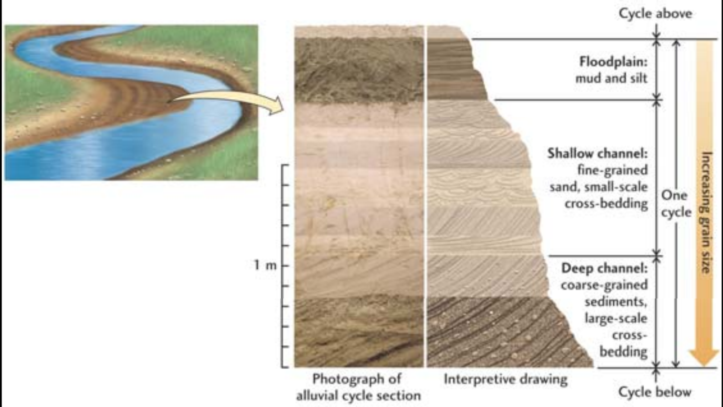
❖The layers dip downward in the direction of down-current. Hence, cross-beds may be used as indicators of ancient current directions.



Formation of Cross bedding

Grains are deposited on the lee side of the dune

River sediment : Cross-Bedding



Cross bedding in "Valley of Fire"

The rock, mostly sandstone, was formed when huge sand dunes compacted over time, with layers of different colors being created as sand and water mixed with different minerals was moved from different places into the same final location. The red is caused by iron oxide

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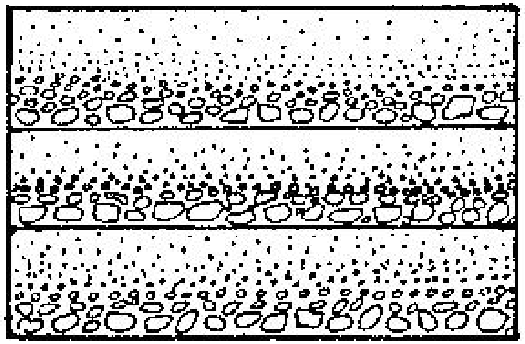
Graded bedding

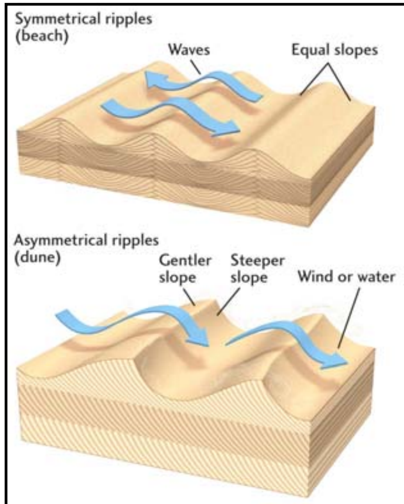
Coarse grains at base and progressively finer grains towards the top.



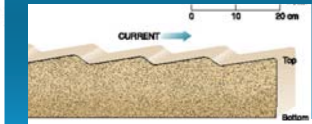
Graded bedding (contd.)

Ripple Marks

- Ripple marks are small undulations formed on surface of sediment layer by moving wind or water.
- Symmetric ripple marks are produced by waves or oscillating water moving in both directions
- Asymmetric ripple marks form in unidirectional currents (such as in streams or rivers). Asymmetric ripples have a steep slope on the downstream side, and a gentle slope on the upstream side. Because of this unique geometry, asymmetrical ripples in the rock record may be used to determine ancient current directions.



Symmetric ripple marks are produced by waves or oscillating water moving in both directions (beach sand)



Asymmetric ripple marks form in unidirectional currents (such as in streams or rivers).

Ripple Marks on sand

Ripple Marks

Mud-cracks

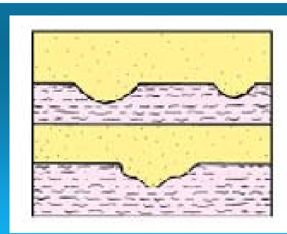
❖Mud cracks are a polygonal pattern of cracks produced on the surface of mud (sediment) as it dries.

❖Mud cracks represent the top of the strata.

Scour Marks

❖Depressions or erosional features formed as a current flows across a bed of sand.

❖Younger sediment may be deposited over the scoured layer, filling the depressions.



Fossils (Organic Structures)

❖Fossils are remains of plants or animals which are usually found in sedimentary rocks.

❖They include hard parts (shells, bones, skeletons) as well as impressions.

Sorting

Sorting: measure of the variation in the range of grain sizes in a clastic rock or sediment.

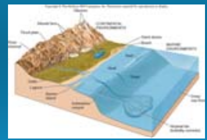
•Well-sorted (uniform) sediments indicate that they have been subjected to prolonged water or wind action.

•Poorly-sorted (graded) sediments are either not far-removed from their source or deposited by glaciers.

Sedimentary Rock Interpretation

Sedimentary rocks give important clues to the *geologic history* of an area

- *Source area*
  - Locality that eroded and provided sediment
  - Sediment composition, shape, size and sorting are indicators of source rock type and relative location
- *Depositional environment*
  - Location where sediment came to rest
  - Sediment characteristics and sedimentary structures (including fossils) are indicators
  - Examples: glacial valleys, alluvial fans, river channels and floodplains, lakes, deltas, beaches, dunes, shallow marine, reefs, deep marine



Types of Sedimentary Rocks based on Depositional Environment

- **Marine – Sea Deposited**
- **Lacustrine – Lake Deposited**
- **Glacial – Glacier Deposited**
- **Eolian – Wind Deposited**
- **Fluvial – River Deposited**

Organic Sedimentary Rock

Organic sediments may be derived from biological activities of various organisms, living in water bodies. Organic Limestone (coral reef) is formed from the calcium carbonate structures secreted by various sea organisms.

Another type of organic sediment forms where dead plant material accumulates in thick layers. With a small degree of compaction, this becomes peat; after much longer and deeper burial, it becomes coal.

Diversity of Corals

Coral reefs form some of the most diverse ecosystems on Earth. They occupy less than 0.1% of world's ocean surface, yet they provide a home for 25% of all marine species.

Source: Toby Hudson (Wikimedia Commons)

Chemical Sedimentary Rock

Sediments , in solution in water bodies, may ultimately get precipitated resulting in formation of chemical sedimentary rocks.

Pure limestone consists predominantly of mineral Calcite ($CaCO_3$) but impurities in the form of SiO2 or MgCO3 may be present. Limestones are likely to form from sea-water.

Rock Gypsum ($CaSO_4$) and Rock Salt (NaCl) belong to a special class of chemical sediments known as Evaporites, which develop by evaporation from sea water or salt water lakes.

Types of Sedimentary Rocks based on Grain Size

- Fine grained – Grain Size < 1 mm
- Medium grained – Grain Size = 1-5 mm
- Coarse grained – Grain Size > 5 mm

Shape of Grains constituting Sedimentary Rocks

Shape of grains constituting sedimentary rocks may give important information.

- Minerals which are hard and resistant to weathering such as Quartz will form angular grains.
- Rivers produce rounded grains (roundness increases with transported distance) while winds produce angular grains. Grains carried by glacier will be more flat.
- More amount of sediment transportation means more roundness.

Shale

Shale is a fine-grained, clastic sedimentary rock. Shales are most abundant, forming 70 to 80% of all sedimentary rocks. Typical color is gray, however variable amounts of minor constituents may alter the color of the rock. Grain shape can only be recognized through electron microscope or by X-Ray analysis.

- Common minerals present in shales are Kaolinite, Montmorillonite, Illite (clay minerals), however other minerals such as Mica, Quartz (silt sized particles) may also be present.
- Shales are generally soft and break easily. The linear arrangement of flaky minerals parallel to bedding, enables the shale to break along thin flat fragments.
- Shales contain organic matter.

Shale

(c) Shale

Limestone

Limestone is a (chemical or organic) sedimentary rock composed largely of the minerals calcite and aragonite, which are different crystal forms of calcium carbonate (CaCO3). They are usually marine in origin. Limestone makes up about 10% of the total volume of all sedimentary rocks. Limestone has numerous uses as a building material.

- Limestones are usually fine-grained compact rocks, however organic limestones (coral reef) may sometimes be loosely packed which exhibit coarse textures.
- The solubility of limestone in water and weak acid solutions leads to karst landscapes, in which water erodes the limestone over thousands to millions of years. Most cave systems are through limestone bedrock.

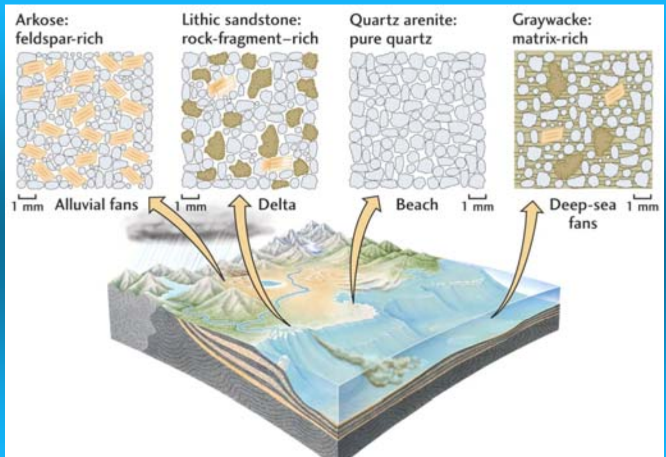
Limestone Formations

Sandstone

Sandstone is a clastic sedimentary rock composed mainly of sand-sized grains. It is the second most abundant (15%) sedimentary rock next to Shale. Some varieties used as building material.

- Quartz is the chief mineral constituent of sandstone. However, Feldspars, Mica may also be present.
- Arkoses are sandstones rich in Feldspar. Possibly derived from granitic rocks.
- Greywacks are usually argillaceous in character, where clayey matter forms the cementing matrix. They have poor strength.

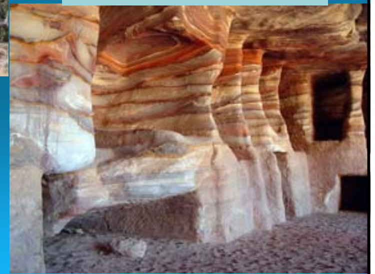
Mineralogy of Sandstone

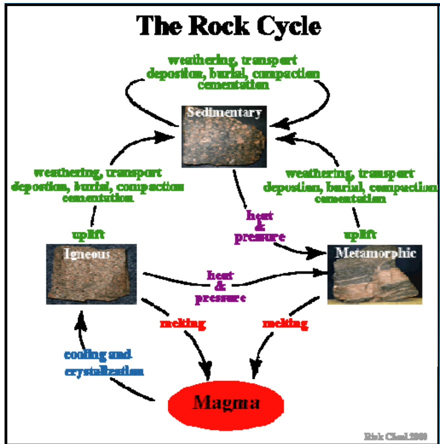


Sandstone Formations

Navajo Sandstone, Utah, USA

Sandstone Rock-cut tombs in Petra, Jordan





Clastic sedimentary rocks can be made up of "multicycled" particles.

i.e., have passed through the rock cycle several times.

Metamorphic Rocks

New rocks formed by changes in texture, mineralogical, or chemical composition taking place in the solid state of pre-existing rocks

Metamorphism

Metamorphism is a natural process where by the existing rocks are altered under conditions of high pressure and temperature associated with depths several thousand metres beneath the surface. It involves partial or complete recrystallization of minerals over long periods of time.

Also, the formation of metamorphic rocks takes place in the solid state, although some kinds of metamorphic processes take place in the presence of hot liquids and gases, chiefly water.

Metamorphism (contd.)

Any rock type which has become stable with respect to its surroundings does not normally undergo any change in it, unless the surrounding conditions get effectively altered. This stable rock, which is in equilibrium with its surroundings, will, however, not remain in equilibrium, as soon as some effective changes are produced in its surrounding conditions, in the form of changes in its surrounding temperature, pressure or environment. Therefore, in order to bring a new equilibrium with respect to the new surrounding conditions, the rocks will undergo certain changes. The extent of changes so produced, will depend upon the nature of the rock, and also upon the extent of changes produced in the rock surroundings.

Metamorphic Rocks from Sedimentary Rocks

Table 4.6. List of Sedimentary Rocks and their corresponding Metamorphic Rocks

Sedimentary Rock	*Metamorphic Conversion*
Conglomerate	Gneiss and Schist
Sandstone	Quartzite
Shale	Slate, Phyallite and Schist
Limestone	Marble and Schist

Metamorphism of Metamorphic Rocks

Slate ⇒ Phyllite ⇒ Schist

Metamorphic Rocks from Igneous Rocks

Table 4.7. List of Igneous Rocks with their corresponding Metamorphic Conversion Rocks

Igneous Rock	*Metamorphic Conversion*
Coarse-grained rocks, such as Granites, Syenites, etc. (Acidic Rocks)	Gneiss.
Fine-grained rocks, such as Felsite, Tuffs, etc. (Basic Rocks)	Schists, Slates, etc.
Ferromagnesian rocks, such as Dolorites, Basalts, etc. (Ultra Basic Rocks)	Schists, etc.

Agents of Metamorphism

- PRESSURE
- HEAT
- CHEMICALLY ACTIVE FLUIDS

PRESSURE

There are two types of pressures to which the Earth's rocks are subjected to: (i) static pressure (ii) dynamic or lateral pressure.

The static pressure is the vertical pressure caused by the over-burden above a particular rock.

The dynamic or lateral pressure is caused by the Earth's movements during orogenic or mountain building period. This dynamic pressure produces shearing stresses, and is much more effective than the static pressure in producing changes in the rock masses, as shown in the production of folds and accompanying structures such as faults, joints, foliations etc. This pressure, in association with chemically active water and with or without much heat, may produce extreme effects of metamorphism

HEAT

The heat involved in metamorphism may come from two important sources, such as, (i) heat from the interior of the earth, which increases with depth; and (ii) heat from the intrusions of molten magmas.

Sometimes, the earth movements may depress the rocks downwards after their formation, resulting in higher temperature surroundings, and thus becoming an indirect source of heat supply.

In any case, whatever may be the source, heat is a very effective agent of metamorphism. Besides producing its direct action, it greatly increases the solvent action of fluids or solutions, which promotes the formation of new minerals.

HEAT (Contd.)

Heat from the interior of earth, provides a very potent agent of metamorphism at sufficient depths, and is thus able to cause widespread metamorphic changes in the surrounding rocks producing regional metamorphism.

Heat from intrusive magmas, may produce metamorphic changes to only a limited scale, on the rocks which are at shallower depths, thus producing contact or local metamorphism.

CHEMICALLY ACTIVE FLUIDS

The presence or absence of chemically active fluids (liquids and gases) beneath the Earth's surface, probably, plays the most definite and decisive role in the process of metamorphism.

The various rocks of the Earth may contain certain entrapped liquids and gases within their pores. Water is the most important of all such liquids, and may be of meteoric or magmetic origin. It may be present as liquid or as vapour. When this water is at very high temperatures, it becomes chemically active, and acts as a solvent of nearly all rock-forming minerals, slowly transferring mineral matter from one point to another, which aids in recrystallisation of the rock minerals, and thus resulting in the formation of new minerals.

CHEMICALLY ACTIVE FLUIDS (Contd.)

Water as a catalyst during metamorphism; aids the exchange of ions between growing crystals.

Water is sometimes aided by substances like fluorine, bromine, carbon dioxide, hydrofluoric acid, other gases, etc. ; which may be present and carried by water in solutions.

These chemically active solutions produce many important changes in the rocks by producing various new minerals, and thus bringing about metamorphism.

Metamorphic Grade

Refers to the intensity of metamorphism.

High grade: High temperature, and pressure

Low grade: Low temperature and pressure

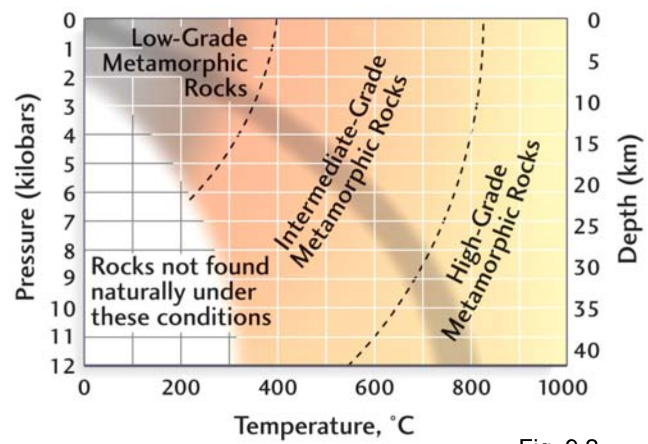


Fig. 9.2

Metamorphic Reactions

Mineralogical changes (e.g., clay to mica):
Series of complicated reactions that depends on pressure, temperature, and composition
Common metamorphic minerals include amphiboles, garnet, mica, staurolite, and kyanite.
Textural changes: recrystallization (grain boundaries become more compact) and foliation (preferred orientation of minerals)

How Much Can a Rock Change?

Amount of change during metamorphism depends on:

- Grade of metamorphism
- Duration of metamorphism
- Composition of the rock

Texture of Rock

Texture refers to the size, shape, and arrangement of the crystals or grains composing the rock.
The texture of a rock is a consequence of the physical and chemical conditions under which it formed and, perhaps, some of the processes that have acted on the rock since that time.

Changes in Texture Due to Recrystallization

- Grain size can increase or decrease
- Shape of grains can change
- Orientation/arrangement of mineral shifts

Foliation of Metamorphic Rocks

The development of foliations is such an important feature of many metamorphic rocks, that it is a general practice to classify the rocks on the basis of development' or 'no development' of foliations. Hence, we have the two types of rocks, *viz.*

(1) **Foliated rocks**, which do have foliations, such as *Slates, Phyllites, Schists*, and *Gneisses* of different kinds.

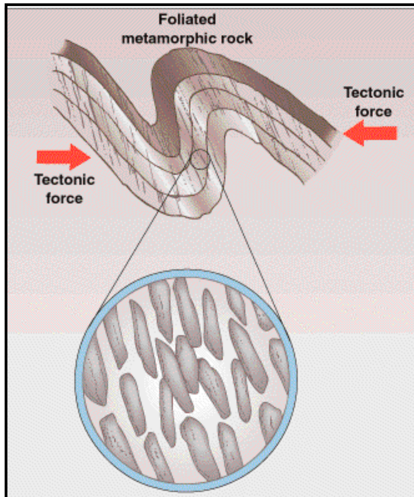
(2) **Non folisated rocks**, which do not have any foliations, such as *Quartzite*, Marbles, *Hornfels*, etc.

Foliation (contd.)

Metamorphism generally results in the production of secondary parallel structures, which resemble more or less closely to bedding or stratification of sedimentary rocks, and along which the rocks tend to split with more or less ease. This development of parallel structure is called foliation or rock cleavage. Important metamorphic rocks like Slates, Schists, and Gneisses are found to have foliations.

Foliation (Contd.)

Although the parallel foliations developed in metamorphic rocks, resemble the stratification of sedimentary rocks and that of certain igneous rocks, it must be differentiated from them. The foliations is entirely a secondary structure, developed in metamorphic rocks due to the parallel arrangement of minerals, in layers of contrasting mineralogical composition, and is thus not connected with bedding and stratification of sediments. The common minerals found arranged in layers are micas, chlorite, tourmaline, hornblende, etc.



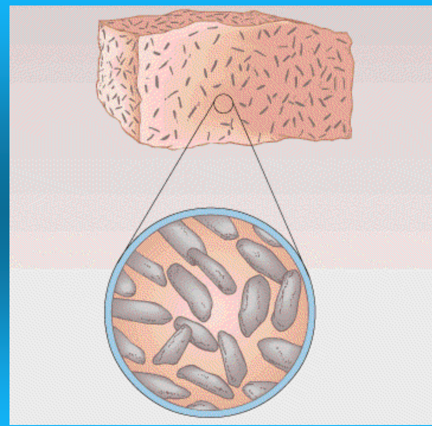
Foliated Metamorphic Rock

During metamorphism, platy minerals aligns themselves perpendicular to the forces that fold the rocks.

Nonfoliated Metamorphic Rocks

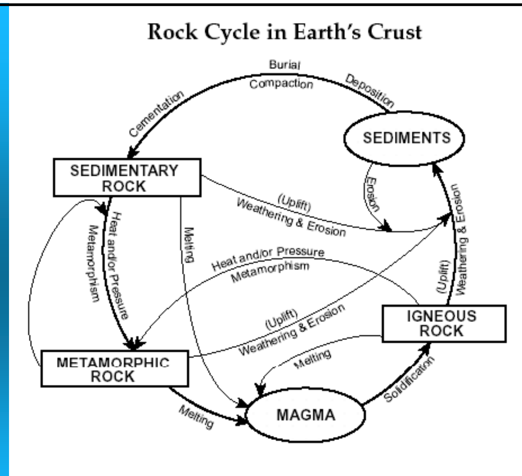
Non foliated metamorphic rocks do not have any foliation.
These rocks are composed of randomly oriented mineral particles.
These rocks do not break in parallel layers, it breaks in angular fragments.

Nonfoliated Metamorphic Rock



Textures of Metamorphic Rocks

Gneissose: Coarsely foliated, Folia straight or wavy
Schistose: Finely foliated, minerals visible
Slaty: Very fine foliated, easy splitting in parallel planes.
Hornfelsic: Unfoliated, fine grained
Granoblastic: Unfoliated, granular texture.



Marble

Marble is a nonfoliated metamorphic rock resulting from metamorphism of sedimentary carbonate rocks, most commonly limestone or dolomite rock. It is composed mainly of calcite or magnesium/calcium silicates. Marble is commonly used for sculpture and as a building material.

Metamorphism causes recrystallization (larger crystals) of the original carbonate mineral grains. The resulting marble rock is typically composed of an interlocking mosaic of carbonate crystals. Primary sedimentary textures and structures of the parent carbonate rock are modified or destroyed.

Marble (contd.)

Pure white marble is the result of metamorphism of a very pure (silicate-poor) limestone or dolomite protolith. The characteristic swirls and veins of many colored marble varieties are usually due to various mineral impurities such as clay, silt, sand, iron oxides, or chert which were originally present as grains or layers in the limestone. Green coloration is often due to serpentine resulting from originally high magnesium limestone or dolostone with silica impurities. These various impurities have been mobilized and recrystallized by the intense pressure and heat of the metamorphism.

The Taj Mahal is entirely clad in marble.

Slate

Slate is a fine-grained, foliated metamorphic rock derived from an original shale-type sedimentary rock through low-grade regional metamorphism. It is the finest grained foliated metamorphic rock.

Foliation may not correspond to the original sedimentary layering, but instead is in planes perpendicular to the direction of metamorphic compression.

Slate (contd.)

“Slaty cleavage“ is caused by strong compression causing **fine grained clay flakes to regrow in planes perpendicular to the compression.**

When expertly "cut" by striking parallel to the foliation, with a specialized tool in the quarry, many slates will form **smooth flat sheets of stone** which have long been **used for roofing and floor tiles** and other purposes

Slate / Use of Slate as Roof Tiles

Slate

Use of Slate as Roof Tiles

Gneiss

Gneiss is a common and widely distributed type of rock formed by **high-grade regional metamorphic** processes from pre-existing igneous or sedimentary rocks. It is often foliated (composed of layers of sheet-like planar structures).

Unlike slate and schist, gneiss does not preferentially break along planes of foliation because less than 50% of the minerals formed during the metamorphism are aligned in thin layers. The **layers do not have a constant thickness, and are discontinuous**.

Gneiss (contd.)

The **foliations are characterized by alternating darker and lighter colored bands**, called "gneissic banding". The minerals are arranged into layers which appear to be bands, when cross-section of the rock is viewed. The **darker bands have relatively more mafic minerals** such as biotite, pyroxene (augite) and amphibole . The **lighter bands contain relatively more felsic minerals** such as feldspar (orthoclase, plagioclase) and quartz.

Gneiss (contd.)

Gneissic rocks are usually medium- to coarse-foliated and are largely recrystallized but do not carry large quantities of micas, chlorite or other platy minerals. Gneiss may be named after parent rocks such as granite gneiss, diorite gneiss, etc.

Not all gneiss rocks have detectable banding however.

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Granitic Gneiss

Gneiss

CE 203 slides by T.M.Al-Hussaini 207

Schist

Schist is medium grade foliated metamorphic rock, formed by the metamorphosis of mudstone / shale, or some types of igneous rock, to a higher degree than slate and phyllite, i.e. it has been subjected to higher temperatures and pressures. The resulting foliation is coarser and more distinct than that of slate and phyllite due to the higher degree of crystallisation of mica minerals (biotite, chlorite, muscovite) forming larger crystals (visible), and is often referred to as schistosity. These larger crystals reflect light so that schist often has a high lustre, i.e. it is shiny.

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Schist (contd.)

Porphyroblasts are common in schist, and they provide information on the temperature and pressure conditions under which the rock formed. There are many varieties of schist and they are named for the dominant mineral comprising the rock, e.g. mica schist, chlorite schist (green due to high chlorite content), garnet schist etc.

Schists are generally weak rocks, which split readily into flakes. Generally used as a decorative rock, e.g. walls, gardens etc; high percentage of mica group minerals precludes its use in the construction and road industries

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Schist (contd.)

Most schists have been derived from clays and muds which have passed through a series of metamorphic processes involving the production of shales, slates and phyllites as intermediate steps. Certain schists have been derived from fine-grained igneous rocks such as basalts and tuffs. Most schists are mica schists, but graphite and chlorite schists are also common.

Schist (contd.)

Hornfels

Hornfels is a fine-grained metamorphic rock formed by the contact between mudstone / shale, or other clay-rich rock, and a hot igneous body. This heat-altered rock conversion process is termed contact metamorphism. Because pressure is not a factor in the formation of hornfels, it lacks the foliation seen in many metamorphic rocks. Granular, platy or elongate crystals are randomly oriented. Pre-existing bedding and structure of the parent rock is generally destroyed.

Hornfels (contd.)

It is often difficult to identify hornfels without microscopic observation, or knowledge of its association with a magma body. Under a microscope the structure of hornfels is very distinctive, with fine mineral grains fitting closely together like the fragments of a mosaic or a rough pavement.

Used as aggregate in construction and road industries.

Hornfels (contd.)

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Quartzite

Quartzite is a **medium grained** metamorphic rock formed when quartz-rich sandstone or chert has been exposed to high temperatures and pressures. Such conditions fuse the quartz grains together forming a dense, hard rock. Quartz grains are visible. **Quartzite generally comprises greater than 90% percent quartz**, and are the largest and purest concentrations of silica in the Earth's crust.

Used as aggregate in construction and road industries.

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Quartzite (Contd.)

Quartzite may **break across quartz grains**, whereas the sandstone breaks around quartz grains. Quartzite also tends to have a sugary appearance and glassy lustre. Pure quartzite is white, however variety of colours displayed by quartzites are a consequence of minor amounts of impurities. Although quartzite can sometimes appear superficially similar to marble, a piece of **quartzite will not be able to be scratched by a metal blade**, and quartzite will not fizz on contact with dilute hydrochloric acid. It is generally **gritty to touch**

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Quartzite (contd.)

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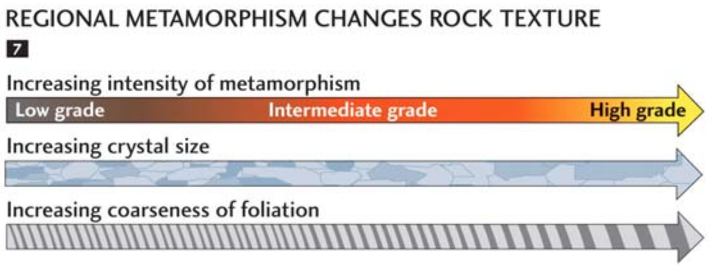


Fig. Story 9.4

Low grade	**Slate**
	Phyllite
	Schist
	Gneiss
High grade	**Migmatite**

Fig. Story 9.4

Textures of Metamorphic Rocks

Gneissose: Coarsely foliated, Folia straight or wavy. Mineral grains are coarse and easily identifiable. Chief minerals include feldspar, quartz, mica etc. Lithologically unlike layers of minerals are arranged in more or less parallel bands. Example: Gneiss.

Schistose: Finely foliated, minerals visible. Minerals are mainly platy or rod like chiefly mica, chlorite, amphibole. Evenly foliated structure, due to which the rock often splits easily. Example: Schist.

Textures of Metamorphic Rocks

Slaty: Very fine foliated. Easy splitting in parallel planes due to parallelism of microscopic crystals of platy minerals chiefly mica. Dense fine-grained rock, which has the property of splitting into thin even slabs. Example: Slate

Hornfelsic: Unfoliated or faintly foliated, fine grained. Formed by partial or complete recrystallization of fine grained rocks such as shale, slate, schist in narrow belts around igneous intrusions. Thermal or contact metamorphism. Example: Hornfels

Textures of Metamorphic Rocks

Granoblastic: Unfoliated or faintly foliated, granular texture. Minerals are large enough to be identified without microscope and are equidimensional such as quartz, feldspar, garnet, pyroxene. Such structures are generally produced by thermal and plutonic metamorphisms. Example: Marble, Quartzite.

Metamorphism

- high enough temperature & pressure to "change" rocks
  but not high enough to melt rocks
  …changes to rocks occur in the **solid-state**…
- hot, reactive fluids also contribute
- old minerals, unstable under new P, T conditions, re-crystallize into new minerals
- new rocks are metamorphic rocks
- metamorphism occurs at depth; cannot see metamorphic rocks unless they are uplifted

Controlling factors

- parent rock composition
- temperature and pressure during metamorphism
- tectonic forces
- fluids

no new material is added to rock during metamorphism

metamorphic rock will have similar composition to parent rock

if parent material contains only one mineral

resultant metamorphic rock will only have one mineral
--mineral will be recrystallized (texture changes)--

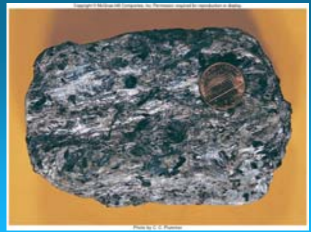
limestone ($CaCO_3$) ⟶ marble ($CaCO_3$)

if parent material contains many minerals…

…old minerals will recombine to form new minerals

clay, quartz, mica, and volcanic fragments in a sandstone will combine to form new metamorphic minerals

example is garnet: which grows during metamorphism



garnet schist (metamorphic rock)

Temperature during metamorphism

- heat from Earth's deep interior
- all minerals stable over finite temperature range
- higher temperatures than range cause melting (and therefore generates *igneous* rocks)

Example of effect of heat

think about mixing flour, yeast, water, salt….

….nothing happens until they have a heat source and then they make bread

Pressure during metamorphism

pressure is proportional to depth in the Earth

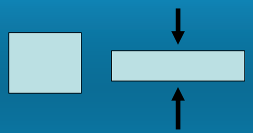
increases at ~1 kilobar per 3.3 km

high pressure minerals:
more compact and dense

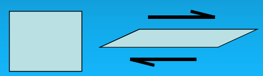
Tectonic forces

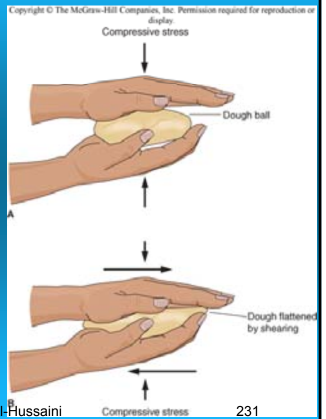
lead to forces that are not equal in all directions (differential stress)

compressive stress
causes flattening at 90° to stress

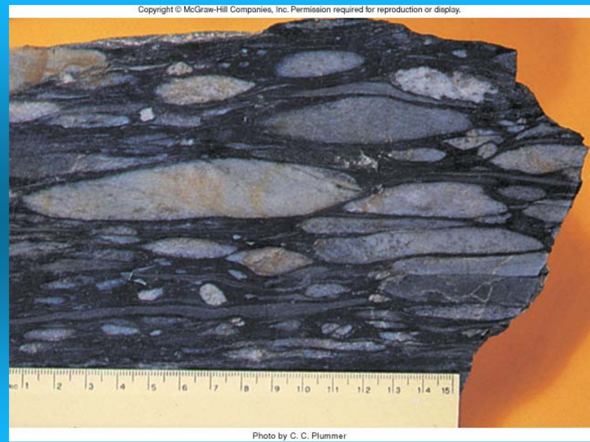


shearing (hands rubbing together)
causes flattening parallel to stress





Flattened pebbles in metamorphic rock



fluids

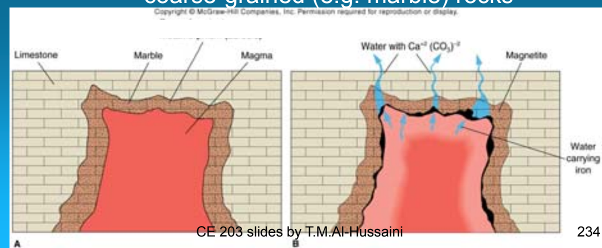
- hot water (water vapor) most important
- heat causes unstable minerals to release water
- water reacts with surrounding rocks and transports dissolved material and ions

time

- metamorphism may take millions of years
- longer times allow new minerals to grow larger --coarser grained rocks

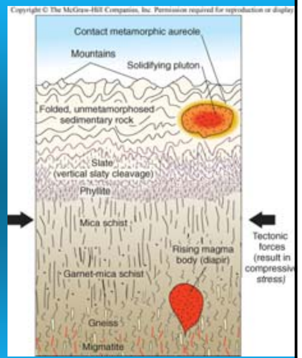
Contact metamorphism

- occurs adjacent to magma bodies intruding cooler country rock -- “contact”
- produces *non-foliated* metamorphic rocks
- happens in a narrow zone of contact
- forms fine-grained (e.g. hornfels) or coarse-grained (e.g. marble) rocks



Regional metamorphism

- occurs over wide region and mostly in deformed mountain ranges
- produces *foliated* metamorphic rocks
- happens at high pressures and over a range of temperature
- increases in pressures and temperatures forms rocks of higher metamorphic grade



Less common types of metamorphism

Partial melting during metamorphism

- produces migmatites, which have both intrusive and metamorphic textures

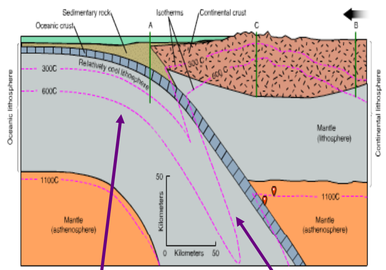
shock metamorphism

- occurs during impact events
- yields very high pressures
- forms "shocked" rocks around impact craters

plate tectonics and metamorphism

regional metamorphism associated with *convergent* boundaries

- pressure increases with depth
- temperature varies laterally
- **different P, T conditions yield different degrees of metamorphism**



temperatures cooler in down-going (subducting) plate (dashed purple line is *isotherm* -- line of equal T)

Table 9.1 Classification of Metamorphic Rocks on Texture

Classification	Characteristics	Rock Name	Typical Parent Rock
Foliated	Distinguished by slaty cleavage, schistosity, or gneissic foliation; mineral grains show preferred orientation	Slate Phyllite Schist Gneiss	Shale, sandstone
Granoblastic (nonfoliated)	Granular, characterized by coarse or fine interlocking grains; little or no preferred orientation	Hornfels Quartzite Marble Argillite Greenstone Amphibolite[a] Granulite[b]	Shale, volcanics Quartz-rich sandstone Limestone, dolomite Shale Basalt Shale, basalt Shale, basalt
Porphyroblastic	Large crystals set in fine matrix	Slate to gneiss	Shale

[a]Typically contains much amphibole, which may show alignment of long, narrow crystals.
[b]High-temperature, high-pressure rock.

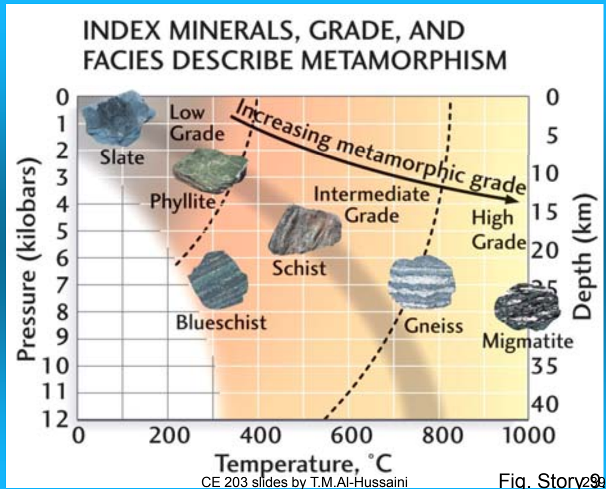


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Fig. Story 9.7b

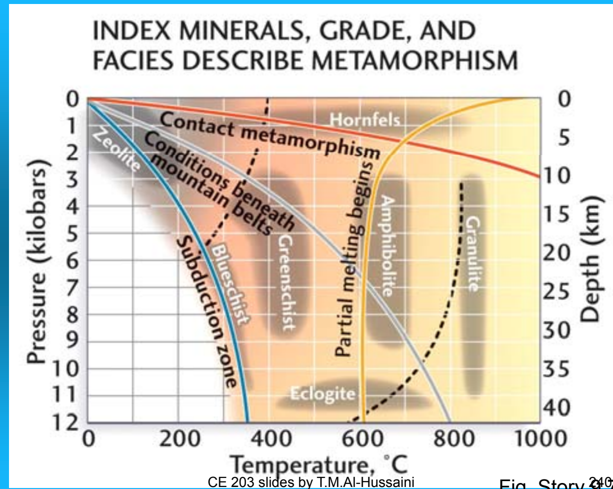

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Fig. Story 9.7d

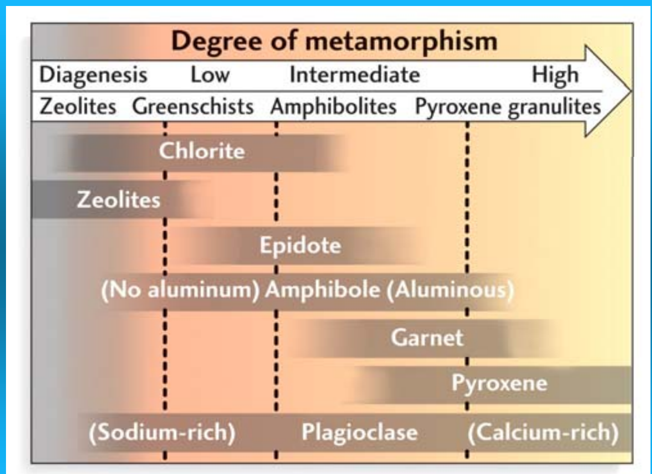

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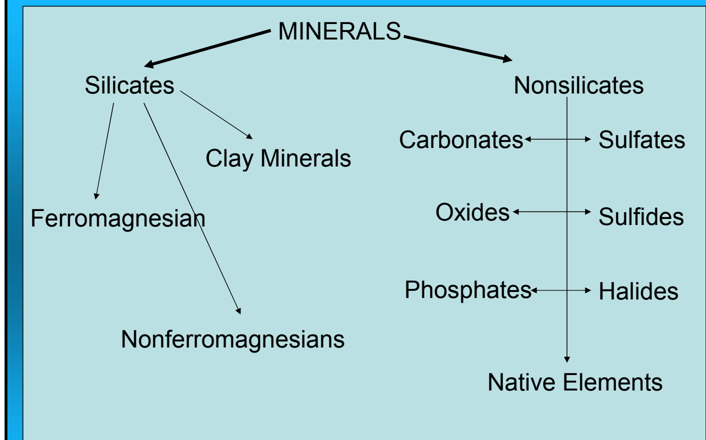
Fig. 9.8a



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Soils

Soil is composed of naturally occurring mineral grains which are separable by gentle mechanical means. Soils are formed by the disintegration (or weathering) of rocks.

Particle size	Soil Classification
COARSE	GRAVEL
Larger than 256 mm	Boulder
256–64 mm	Cobble
64–2 mm	Pebble
MEDIUM	
2–0.062 mm	SAND
FINE	MUD
0.062–0.0039 mm	Silt
Finer than 0.0039 mm	Clay

Soil may be classified based on particle (grain) size

Soil may be classified based on transport as:

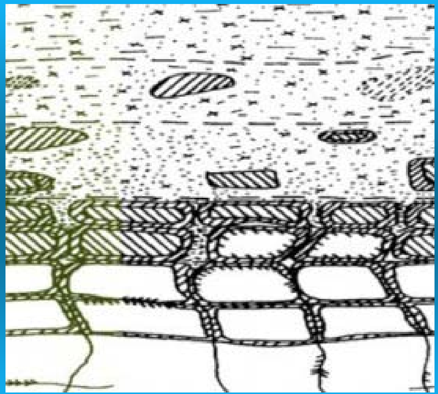
- Residual Soil

- Transported Soil

Residual Soil

- Soil which has been formed by the disintegration (weathering) of parent rock and still occupies the position of the rock where it originally belonged.
- After their formation, they have remained at the same place without undergoing any significant transport.
- The soils typically retain many of the characteristics of the parent rock. In a tropical region, residual soil layers can be very thick, sometimes hundreds of meters on top of un-weathered rock.

Residual Soil



Transported Soil

Any soil which has been transported from its place of origin (parent rock) by water, wind, glacier, gravity or some other agents and has been redeposited in another location.

Transported Soil (contd.)

- Aeolian/Eolian deposits – Soils transported and deposited by winds.
- Alluvial deposit – Soils deposited from suspension in running water.
- Lacustrine deposit – Soils deposited from suspension in quiet fresh water lakes.
- Glacial deposit – Soils transported by big chuncks of ice or glacier
- Marine deposit – Soils that have been deposited from suspension in sea-water.

Wind Erosion

Abrasion

rubbing and grinding action of sand particles blown by wind

Wind Erosion
Aeolian Deposits

Wind Erosion

- Wind picks up soil particles (sand, silt)
- These windborne particles may hit landforms and break those landforms

Wind Erosion

- Deflation –
  Removal of sand and silt sized particles by fast moving wind. Very effective where land is dry and devoid of vegetative cover.
- Abrasion –
  Most of sand driven by winds remain confined in lower layer within about 30 to 60 cm of surface. The rubbing and grinding action of these sand particles causing erosion of landforms is known as abrasion. Due to this reason, cliffs or rocks may be eroded mainly at the bottom.

Wind Transported Soil

- **Aeolian/Eolian deposits – Soils transported and deposited by winds. Wind picks up soil particles (sand, silt). Sand dunes are formed this way in desert environment. Loess is formed by wind-blown silt.**

SAND DUNES

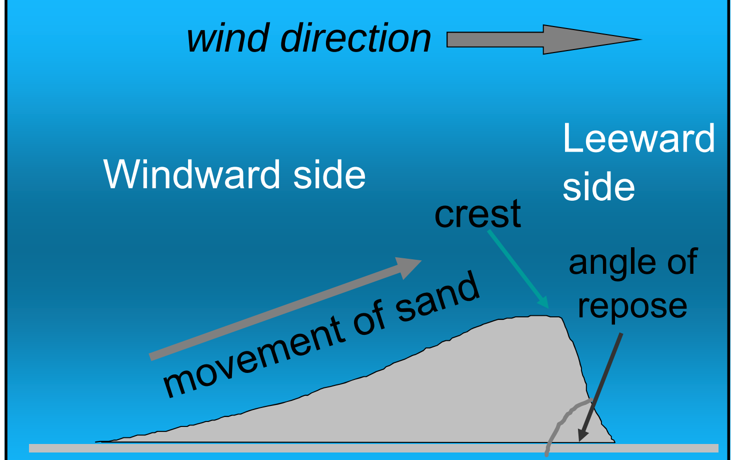
are ridges of wind deposited sand

- Usually 3 to 15 metres high, but can reach 180 metres

The formation of dunes depends on:
- amount of sand
- speed and direction of wind
- occurrence of vegetation

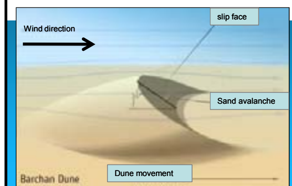
Unless they are stabilized by vegetation or cementation, most sand dunes move slowly (shift position) with time.

Corbis Digital Stock



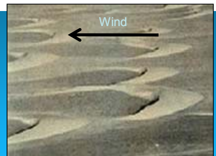
Types of Dunes

- Dunes are formed as mounds or ridges of aeolian sand deposits and are then sculpted by near-surface wind processes, such as **saltation**. Saltation transports sediment up slope on the windward side and once the sediments reach the crest they fall over and accumulate as a steeper slope on the leeward side of the dune, referred to as the **slip face**. This section will cover **barchan**, **transverse**, **longitudinal**, **parabolic**, and **star dunes**.
- **Barchan dunes** are solitary, crescent shaped dunes with their tips pointing downwind. They form where sand source is limited, wind direction is constant, and the ground is void of vegetation. They can reach heights of 30 meters and spread nearly 300 meters.
- **Transverse dunes** are a series of long ridges that are parallel to one another, and are perpendicular to the prevailing wind. They form in areas where the prevailing winds are steady, there is an abundant supply of sand, and vegetation is sparse. They can reach heights of 200 meters and may extend for 100's of kilometers.



http://www.nps.gov/archive/grsa/resources/images/lgformat/barchan.jpg

Barchan Dunes



John McCauley, USGS

Transverse Dunes

John McCauley, USGS

Types of Dunes (contd)

- Longitudinal dunes, also referred to as Seifs are long ridges of sand that form parallel to the prevailing wind. They form in areas where there is moderate supply of sand, and they range in size 5-10 meters tall to 100 meters in height and width.
- Star dunes are complex dunes with a central mound surrounded by radiating points. From above they resemble a star shape. They are formed by shifting wind patterns that create the unique star shape. Star dunes can reach heights of 90 meters and extend outward for over twice their height.
- Parabolic dunes are similar in form to barchan dunes except their tips point into the wind. They form as blow outs where the sand has carved out the sediments and deposited it onto the leeward side. Parabolic dunes form inland from coastal shorelines from sands on the beach.

Star Dune in Namib Desert, Namibia

http://en.wikipedia.org/wiki/Image:Dune_7_in_the_Namib_Desert.jpeg

Longitudinal Dune

Photo: www.googleearth.com Eve, Montana

Loess Deposits

- **Loess is a clastic, predominantly silt-sized sediment deposit, which is formed by the accumulation of wind-blown dust**
- **Loess grains are angular with little polishing or rounding and composed of crystals of quartz, feldspar, mica and other minerals. Loess can be described as a rich, dust-like soil.**
- **Loess deposits are likely to settle on wetting or under construction loads.**
- **Although loess deposits are porous and friable, they may get cemented with time and form vertical surfaces.**

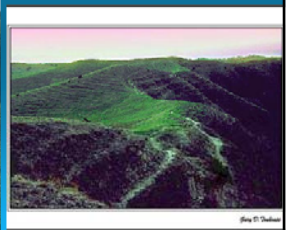
Loess

- Loess deposits are regionally extensive accumulations of windblown silt resulting from thousands of dust storms.
- Loess deposits are generally coarsest and thickest close to their source, and they decrease in thickness and grain size with increasing distance from their source.
- **Loess is not stratified, meaning it lacks distinctive layers.** Instead they are massive accumulations of silt. **Loess deposits range from 30 to >100 meters thick, and they provide very fertile soils for agriculture and farmland.**
- Loess Hills are a rare and unusual landform, found in USA and China.

Photo: SCGS

This loess and sandstone contact is from a quarry near Vicksburg, Mississippi where both deposits are being mined. This loess was sourced from glacial till and blown down the Mississippi River Valley. The person in the picture provides a context for the thickness of the loess deposit.

In the United States, extensive loess deposits occur in South Dakota, North Dakota, Nebraska, Iowa, Missouri, Mississippi, and Illinois. These deposits were sourced from glacial sediments. **Loess hills** in western Iowa are made up of windblown soil from the end of the last ice age, they have one of the **highest erosion rates** in the U.S. The word “loess” comes from the word “loose” – meaning loose soil.



Loess Deposits in China

The most extensive loess deposit occurs in western and northern China, it contains sediments blown from the deserts of Central Asia.

Soil erosion has been a problem in the loess plateau in Northern China

Glacier Erosion
Glacial Deposits

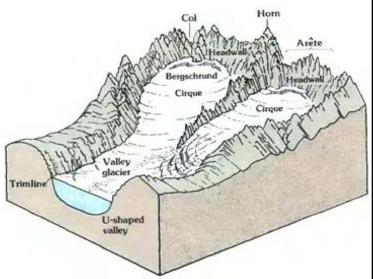
Glacier

Glacier is a huge mass of ice, moving slowly over land. Glaciers are formed from compacted snow in an area where snow accumulation exceeds melting. As thickness of accumulated snow increases, under overburden pressure the snow (specific gravity=0.05) undergoes a series of changes and recrystallizes to form crystalline solid ice (specific gravity=0.9). When the amount of ice becomes large enough in depth (30-50 m) and size, it may slide down under gravity action.

Velocity of glacier movement, as measured in recent times varies from few cm/day to 20 m/day. Glacier movement erodes the earth's top surface and transports rock fragments / soils.

Glacier Erosion

Glaciers are so powerful they can carve valleys and create new landforms. They have a lot of erosive potential as they are thick bodies of ice exerting extreme amounts of pressure.



Two Types of Glacier

- (1) Valley Glacier/ Mountain Glacier: Glaciers formed in the mountains which move down the valley. Valley glaciers may be found in mountain ranges on every continent except Australia, and on a few high-latitude oceanic islands.
- (2) Continental Glacier / Ice sheet: On Earth, 99% of glacial ice is contained within vast ice sheets in the polar regions. They contain vast quantities of fresh water, enough that if both melted, global sea levels would rise by over 70 meters. Huge ice sheets cover most of Antarctica and Greenland. They can be several kms deep.

Valley Glacier

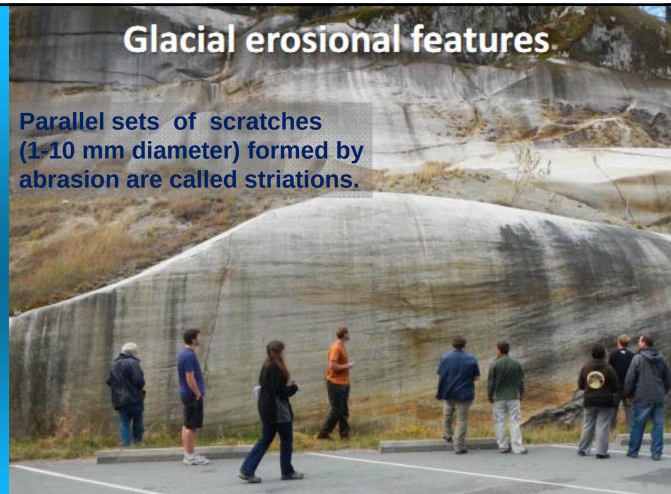
Glacier Erosion

- There are three main types of glacial erosion - plucking, abrasion and freeze thaw.
- Plucking is when melt water from a glacier freezes in the joints of the base-rock and forms a grip. When the glacier moves downhill, it exerts sufficient pressure over the gripped rock and rock is plucked (teared off). This action leaves behind a rough surface.
- Abrasion (rubbing and scratching) occurs when plucked rock pieces frozen to the base and the back of the glacier scrapes the bed rock. The bigger rock fragments produces grooves in the bedrock, while finer sharp fragments produce scratches, sand/silt does the job of polishing.

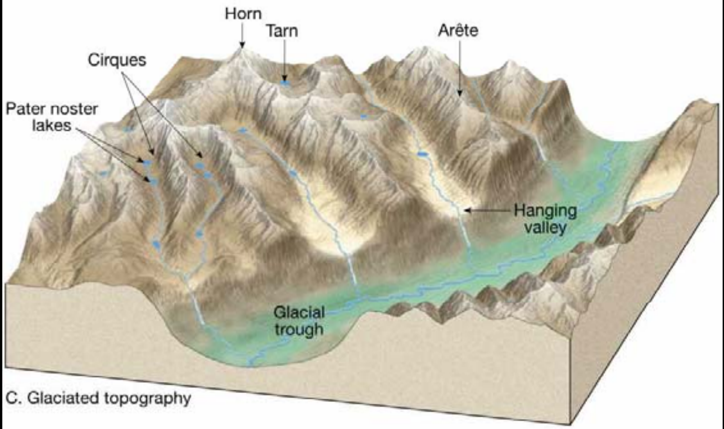
Glacier Erosion (Contd.)

Abrasion can only occur if rock fragments (debris) are present at the ice/rock interface. Clean ice cannot scour its rock bed and the rate of abrasion increases with basal debris concentration, furthermore, the abrading rock fragments must be harder than the bedrock surface beneath.

- Freeze-thaw is when melt water or rain gets into cracks in the bed rock. At night the water freezes, expands and causes the crack to get larger. Eventually the rock will break away.



Glacier Erosion (Contd.)

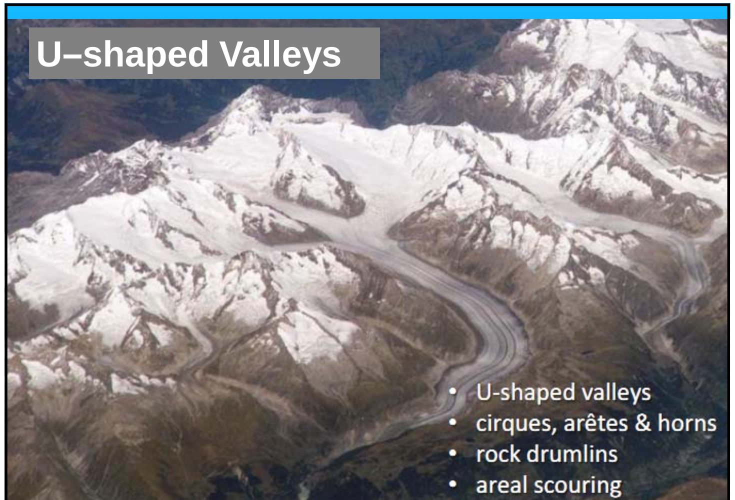


Glacier Erosion (Contd.)

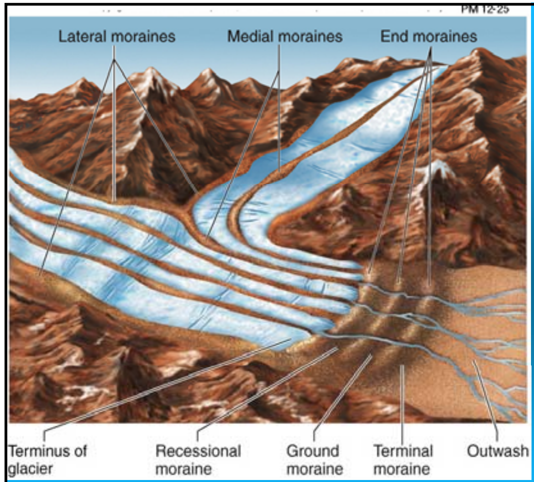
- Glacial Valley: Glacial erosion greatly modifies the shape of the river valley. Erosive action of the glacier carves the valley into a broad U shape instead of the steeper V shape that is produced during the early stages of erosion by rivers. A U shape valley with a flat floor may be good evidence of past glaciation of an area.
- Hanging Valley: Tributary valleys are occupied by smaller glaciers and less deeply eroded than the main valley. The main valley has steep sides formed by main glacier. As a result, the tributary valleys are left hanging above the main valley and with the disappearance of the glaciers form fascinating waterfalls (by stream flow through tributary valley).

Glacier Erosion (Contd.)

- Cirque: Glacier erosion varies along the length, it is most active in the upper reaches. The mass of ice at the top of a glacial valley forms a steep-sided, bowl or amphitheater shaped semi-circular hollow (depression) called a cirque.
- Arête: Spiky high land between two glaciers.
- Tarn: A lake formed in a cirque by overdeepening.
- Fjord: Glacial U-shaped valleys filled with ocean water so as to create an inlet from the ocean.



Glacier Deposits



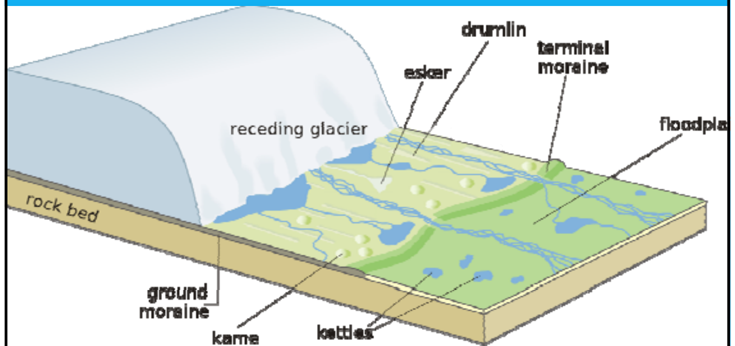
Glacier Deposits

- Moraine: Unsorted and unstratified glacier deposited sediments found at various places of the valley floor.
- Lateral moraine: Lateral moraines are parallel ridges of debris deposited along the sides of a glacier. This debris fall on top of the glacier by frost shattering of the valley walls and/or from tributary streams flowing into the valley. The till is carried along the glacial margin until the glacier melts. Because lateral moraines are deposited on top of the glacier, they do not experience the postglacial erosion of the valley floor and therefore, as the glacier melts, lateral moraines are usually preserved as high ridges.

Glacier Deposits

- Terminal moraine: Moraine deposited at the end point of a glacier. It marks the point of farthest advance of a glacier. Because the toe of glacier is curved, the terminal moraine is also characteristically curved.
- Ground moraine: Moraine deposited on the valley floor as the glacier retreats. Ground moraines are till-covered areas with irregular topography, often forming gently rolling hills or plains
- Kames: Glacial deposits that take the shape of hills or mounds are called kames.
- Eskers: Long, sinuous glacial deposits are called eskers. Eskers are composed of sand and gravel deposited by meltwater streams flowing through ice tunnels within or beneath a glacier.

Landforms created by Retreating Glacier



Glacial Till

- Till or glacial till is unsorted (graded) glacial sediment deposited directly by the glacier. Its content may vary from clays to mixtures of clay, sand, gravel, and boulders. Most particles in the till are angular. This material is mostly derived from the subglacial erosion and entrainment by the moving ice of the glaciers. Bedrock can also be eroded through the action of glacial plucking and abrasion and the resulting clasts of various sizes will be incorporated to the glacier's bed.

Glacial Till (contd.)

Closeup of glacial till. Note that the larger grains (pebbles and gravel) in the till are completely surrounded by the matrix of finer material (silt and sand), and this characteristic is diagnostic of till

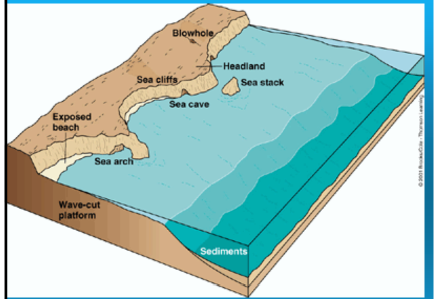
Effect of Climate Change

Most of the glaciers of the world are now retreating due to global warming.

What do you mean by retreating glacier ?

Sea Erosion

Sea Erosion



Wave power causes erosion. Soil particles carried by wave aid the erosion process.

Salts and other chemicals in the water erode coastal rocks

Eroded particles may be carried away (such as long shore drift) and deposited in other areas

Methods of Sea Erosion

Marine water in the form of sea waves and currents, considerably erodes the sea-coast. Even hard rocky coasts are prone to erosion with time. The erosion work by waves is generally accomplished by hydraulic action, abrasion, solution (corrosion).

Hydraulic Action: Simple process of breaking of weak portion of coastal rocks/soils under the influence of pressure created by waves. When a wave impacts a cliff face, air is forced into cracks under high pressure, widening them. Over long periods of time, the growing cracks destabilise the cliff and fragments of rock break off.

Methods of Sea Erosion (contd.)

Abrasion: Process of constant rubbing and grinding action of sandy sea water continuously striking at the rocks at the coast causes erosion. If sand & pebbles are present in the water waves, it will act like sandpaper and erosion will take place faster.

Corrosion: The solvent action of sea-water may erode the rocks which are soluble. Carbon dioxide in the atmosphere is dissolved into water turning it into a weak carbonic acid. Several rocks (e.g., Limestone) are vulnerable to this acidic water and will slowly dissolve into it.

Factors affecting Sea Erosion

Wind: The biggest factor affecting coastal erosion is the strength of the waves breaking along the coastline. A wave’s strength is controlled by its fetch and the wind speed. Longer fetches & stronger winds create bigger, more powerful waves that have more erosive power. Powerful storms can cause lot of instant damage to coasts.

Bathymetry: As waves approach a coastline they lose energy though because friction with the seabed increases. This means that the bathymetry (the underwater elevation) of the ocean or sea bed also impacts the strength of waves. Beaches increase the distance a wave travels before it reaches the coastline’s cliffs and so reduces its energy.

Factors affecting Sea Erosion (contd.)

Landform: Headlands (eg., vertical cliff) may redirect waves around them, reducing their erosive power at one location while increasing it at another.

Weathering: Weathering also plays a role in the rate of erosion by creating weaknesses in rocks that are exploited by the processes of erosion. Freeze-thaw weathering, for example, creates cracks in rocks, increasing the rock's susceptibility to hydraulic action.

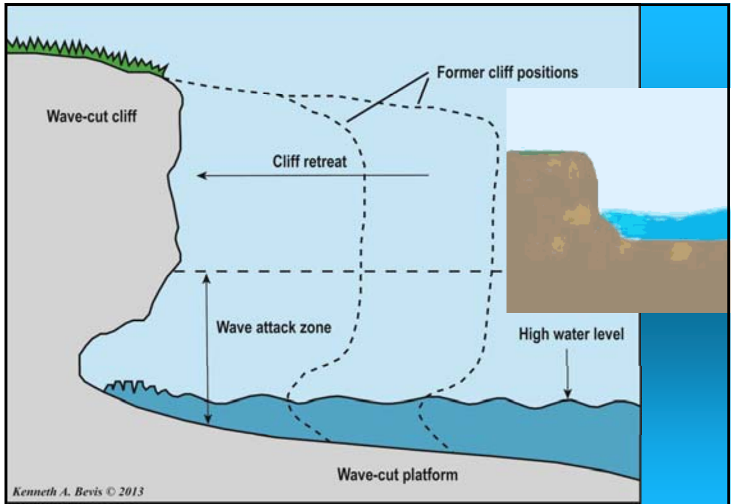
Human Activity: Human activities may have a variety of complex effects on coastal erosion. As an example, dredging, commonly carried out to improve shipping capacities, reduces the amount of energy dissipated from incoming waves and so increases erosion.

Factors affecting Sea Erosion (contd.)

Strength of coastal rocks: Weaker the coastal rocks, more will be the erosion. Hard rocks (e.g., Gabbro) are resistant to weathering & erosion so a coastline made of granite (e.g., Land's End) will change slowly. Soft rocks (e.g., Limestone) are more susceptible to weathering & erosion so a coastline made of chalk (e.g., Dorset) will change relatively quickly. Presence of fissures, fractures in the rocks, and beds of non-cohesive materials such as silt and fine sand accelerates the erosion process.

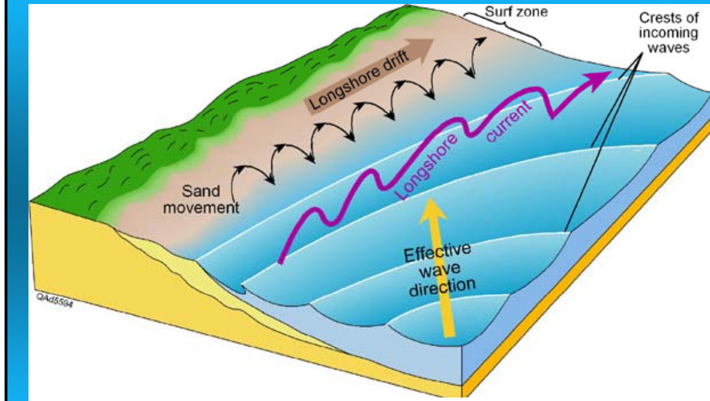
Dip angle: Beds that dip seaward produce gentler cliffs but are less stable because loose material can slide down the bedding planes in mass movements.

Sea Erosion (Formation of Arch)

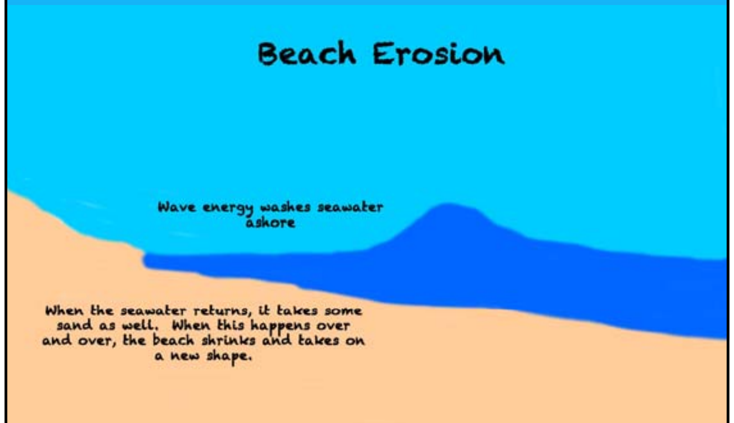


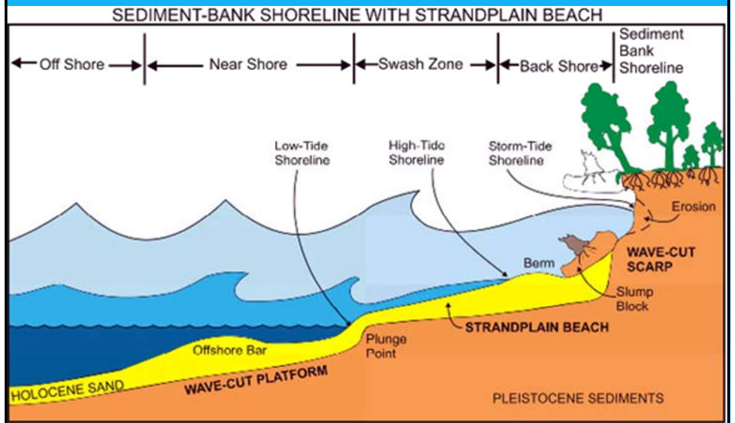
Cliff Erosion by Sea

Sea Transported Soil

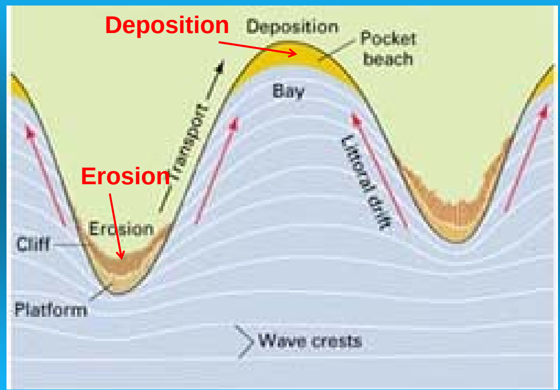


Sand is moved along the beach = longshore drift



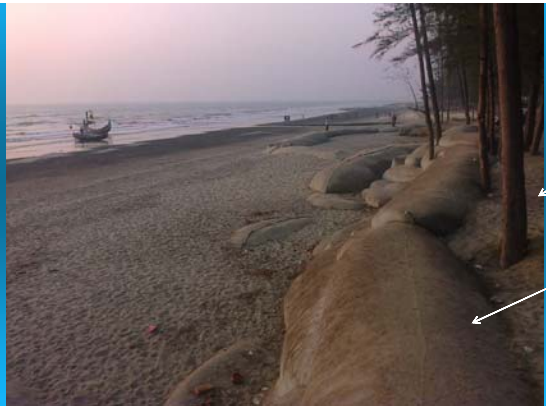


Sea Erosion and Deposition



Cox's Bazar – Teknaf Marine Drive (2013)

Temporary Protection against Sea Erosion Cox's Bazar – Teknaf Marine Drive (2013)

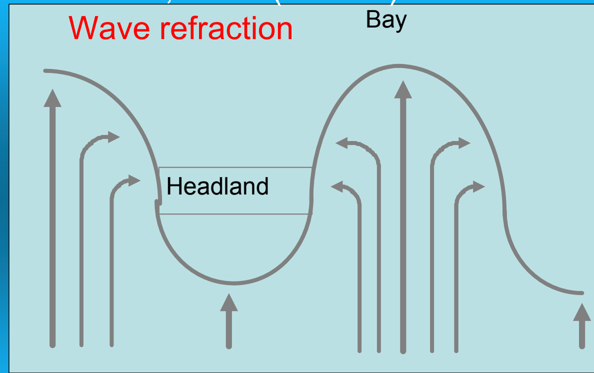


Sea is far away in this stretch of Cox's Bazar – Teknaf Marine Drive (2013)

Wave refraction

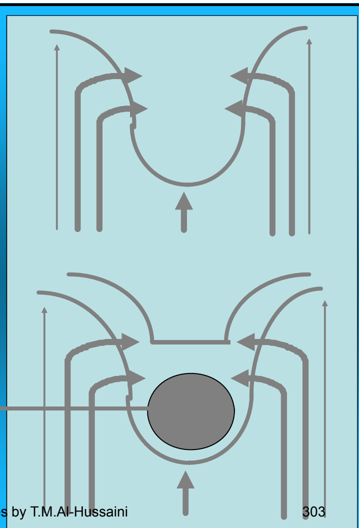
- Close to coast, water gets more shallow
- Waves are slowed down
- If waves arrive at an angle, one part is slower than the rest
- Causes waves to bend = wave refraction

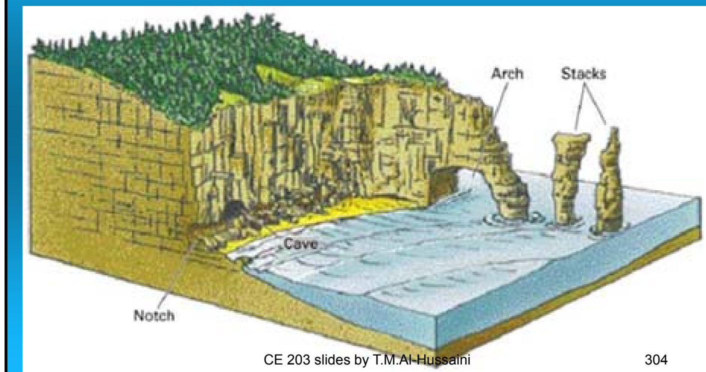
- Waves arriving at bays are slow (deposition)
- At headlands, faster (erosion)



Headlands may be eroded back leaving a remnant (<u>stack</u>)

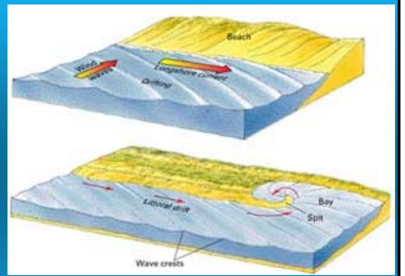
<u>Stack is formed</u>





Longshore drift

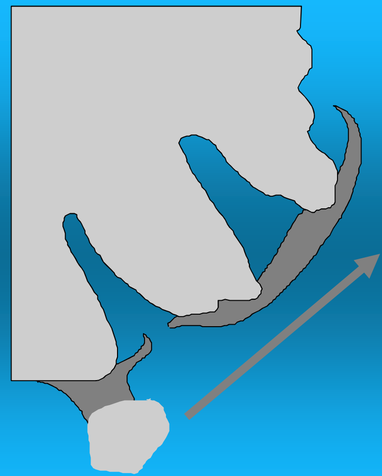
- Waves arrive at a coast at an angle (swash)



Sand is moved along the beach = longshore drift or longshore current

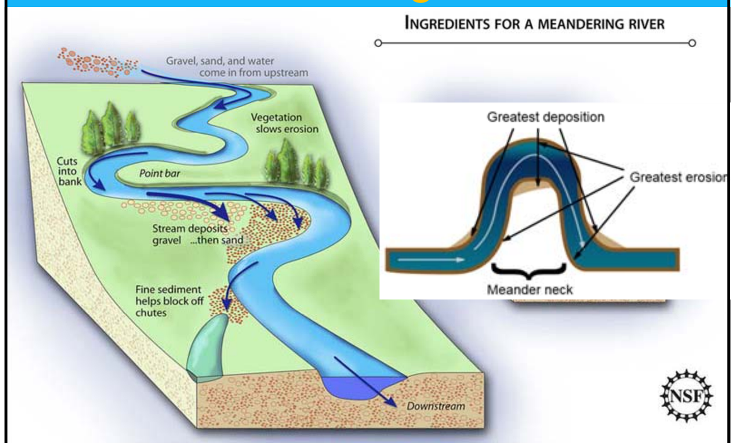
Coastal deposition

- Result of longshore drift and a lot of sediment
- = produces extensions of deposit from the shoreline



River Erosion
River Deposits

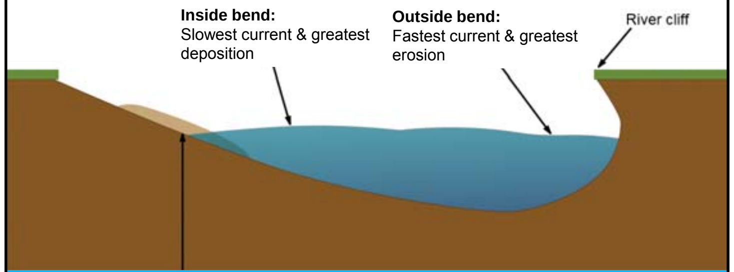
Meandering River



Erosion & Deposition in Meandering River

On the outside bend, the river flows fastest and is most energetic, so lots of erosion takes place. The channel is very deep and concave. River cliffs form on the outside bend as the river erodes laterally.

The river flows much slower on the inside bend so some deposition takes place.The inside bend is shallower with a gentle slip-off slope made of sand or shingles.



Deposition in Braided River

A braided river is divided into smaller sub-channels by small, temporary islands called chars.

Braided channels develop in rivers with a lot of sedimentary load and where the discharge of the river changes regularly.

When the volume of sediment load exceeds the river's capacity or the discharge of the river drops, the river is forced to deposit its sediment in the channel and islands of sediment (chars) form.

Braided River

Deposition in Flood Plains

Floodplains are large, flat expanses of land that form from deposits during flooding on either side of a river. The floodplain is the area that a river floods onto when it's experiencing high discharge.

When a river floods, the river's velocity drops due to friction forcing it to deposit its sediment. The load is deposited across the floodplain as alluvium.

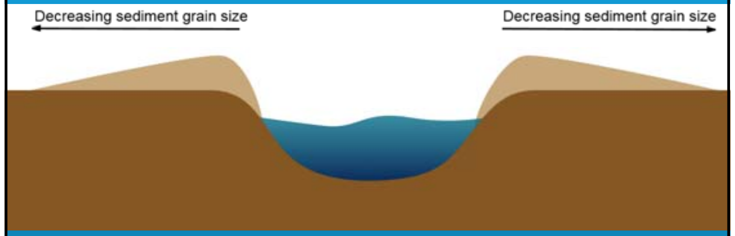
The alluvium is very fertile so floodplains are often used as farmland.

Levees

Levees are natural embankments produced on both banks when a river floods. When a river floods, the largest & heaviest load is deposited first and closest to the river bank, often on the very edge, forming raised mounds. The finer material is deposited further away from the banks causing the mounds to appear to taper off. Repeated floods cause the mounds to build up and form levees.

Levees increase the height of the river's channel and the discharge capacity. Levees can sometimes be burst by the high pressure of the water.

Levees



Delta

Deltas are depositional landforms formed at the mouth of a river where the river meets a body of water with a lower velocity than the river (e.g. a lake or the sea). For a delta to develop, the body of water needs to be relatively quiet with a low tidal range so that deposited sediment isn't washed away and has time to accumulate.

When a river meets a relatively stationary body of water, its velocity falls causing any material being transported by the river to be deposited. Deltas are made up of three sediment beds that have been sorted by the size of the sediment.

Delta (contd.)

The bottomset beds are created from the lightest suspended particles that settle farthest away from the active delta front, as the river flow diminishes into the standing body of water and loses energy. These beds are laid down in horizontal layers and consist of the finest grain sizes. They are deposited beyond the frontal slope in the sea or lake bottom in front of the advancing foreset layers.

Delta (contd.)

Thicker foreset beds are deposited on the front slope of the delta. Thicker foreset beds are deposited in inclined layers over the bottomset beds as the active lobe advances. Foreset beds form the greater part of the bulk of a delta. The sediment particles within foreset beds consist of larger and more variable sizes, and constitute the bed load that the river moves downstream by rolling and bouncing along the channel bottom. When the bed load reaches the edge of the delta front, it rolls over the edge, and is deposited in steeply dipping layers over the top of the existing bottomset beds.

Delta (contd.)

The topset beds of an advancing delta are deposited in turn over the previously laid foresets, truncating or covering them. Topsets are nearly horizontal layers of smaller-sized sediment deposited on the top of the delta and form an extension of the landward alluvial plain. As the river channels meander laterally across the top of the delta, the river is lengthened and its gradient is reduced, causing the suspended load to settle out in nearly horizontal beds over the delta's top.

Most large deltas, built in storm swept or tidally disturbed seas are much more complex than this three bed system.

Ganges–Brahmaputra Delta

- World's largest delta
- One of the most fertile regions in the world
- It covers more than 105,000 km^2 (41,000 sq mi) in Bangladesh and India. Two-thirds is in Bangladesh.

River System in Bangladesh

- Bangladesh is basically a deltaic plain of three mighty rivers, namely the Padma (Ganges), the Jamuna (Brahmaputra) and the Meghna which form one of the largest river systems in the world.
- These three rivers have large number of distributaries, tributaries, sub-distributaries and sub-tributaries. The country has 230 rivers covering a length of about 24,140km.
- About 90 percent of the water carried by our river system, is brought from outside the country. These rivers carry water from an areas of about 600,000 sq. miles of which only 7.5 percent lies in Bangladesh.
- About 90% of the river water in Bangladesh discharges into the Bay of Bengal through the Meghna river estuary.

Alluvial Fan

- An alluvial fan is a fan- or cone-shaped deposit of sediment crossed and built up by streams.
- Fans are typically found where a stream draining from steep narrow valley emerges out onto a flatter plain

CE 203 slides by T.M.Al-Hussaini 323

Sediment Transport by River

- Largest of particles such as boulders are transported by traction. These particles are rolled along the bed of the river, eroding the bed and the particles in the process.
- Slightly smaller particles, such as pebbles and gravel, are transported by saltation. This is where the load bounces along the bed of the river because the river has enough energy to lift the particles off the bed but the particles are too heavy to travel by suspension.
- Fine particles like clay and silt are transported in suspension, they are suspended in the water. Most of a river's load is transported by suspension.
- Solution is a special method of transportation. This is where particles are dissolved into the water so only rocks that are soluble, such as limestone or chalk, can be transported in solution.

CE 203 slides by T.M.Al-Hussaini 324

Sediment Deposition by River

- To transport sediments a river needs to have energy so when a river loses energy it is forced to deposit its sediments. There are several reasons why a river could lose energy. If the river's discharge is reduced then the river will lose energy because it isn't flowing as quickly anymore. This could happen because of a lack of precipitation or an increase in evaporation. Increased human use (abstraction) of a river could also reduce its discharge forcing it deposit its load.
- If the gradient of the river's course flattens out, the river will deposit its load because it will be travelling a lot slower. When a river meets the sea a river will deposit its load because the gradient is generally reduced at sea level and the sea will absorb a lot of energy.

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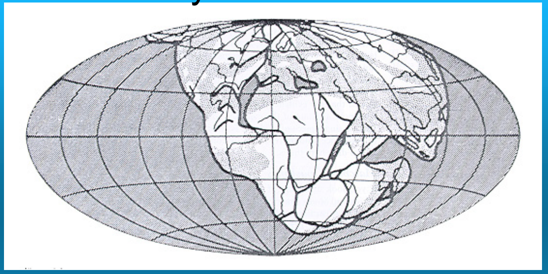
Plate Tectonics Continental Drift

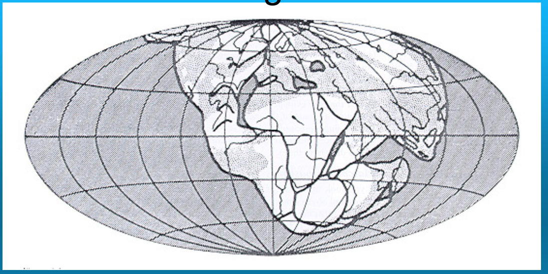
Early Observations



Leonardo da Vinci and Francis Bacon wondered about the possibility of the American and African continents having broken apart, based on their shapes.

This thinking continued up into the early 20th century, to a meteorologist named Alfred Wegener.

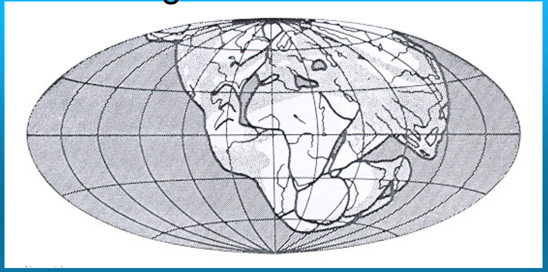
Pangaea



Wegener revived the early idea of *continental drift*, contending that all of the present-day continents were connected, side-by-side, as long ago as the Carboniferous (~300 Myr).

He called the supercontinental mass *Pangaea*, Greek for 'all lands'.

Wegener's Evidence



Wegener's summary was based on a number of careful observations:

-- matching rock, fossil, glacier, and structural relations among different parts of different continents

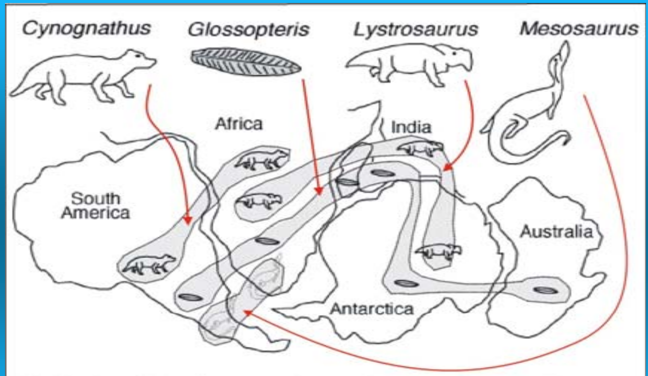
Testing Plate Tectonics

Like any theory, plate tectonics has been rigorously tested, and from a startling array of disciplines.

This model is consistent with the key tests thus far, including:

* sea floor spreading
* paleomagnetic 'paths'
* age structure of the sea floor and continents
* locations and focal depths of earthquakes
* seismic tomography
* hotspot tracks

Continental Drift: Fossil Evidence

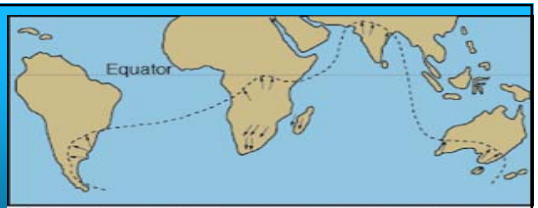


Distribution of fossils across the southern continents of Pangea.

Mesosaurus: purely freshwater reptile
Glossopteris: seeds too large to be effectively wind-transported

Continental Drift: Glacial Evidence

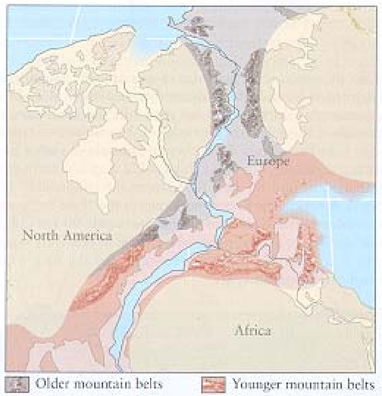
Large ice masses carve grooves in the rocks over which flow.
Such masses tend to flow outward (generally downhill) from a central locality.

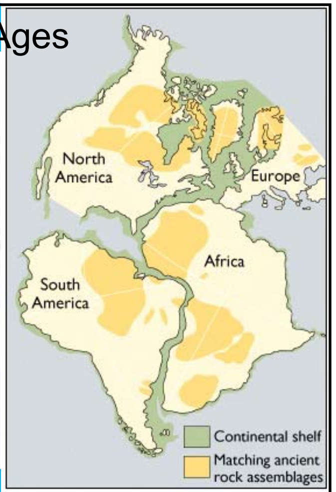


Grooves carved by glaciers (shown by arrows) provided evidence for continental drift. This diagram assumes the continents were in their present-day locations.

The distribution of glacial features can be best explained if the continents were part of Pangaea.

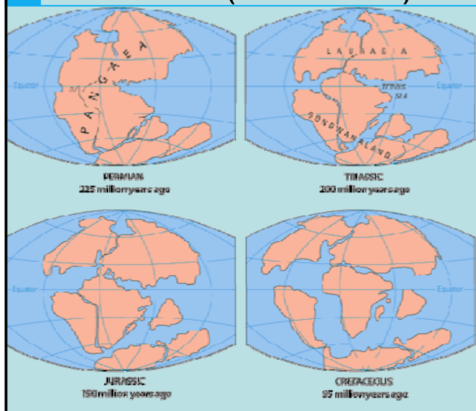
Continental Drift: Rock Ages





Even before geochronology, the relative framework of rock ages showed strong correlation across the Atlantic, as did mountain ranges of similar age.

Hypothesis
"Plates (continents) have moved"



Key Features of Plate Tectonics

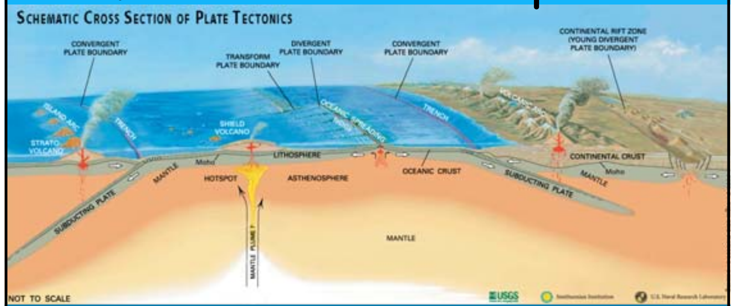
(1) The Earth's crust is constantly being created and destroyed (recycled).

(2) Ocean crust, formed at *divergent margins*, is mafic and dense.

(3) As ocean crust ages and cools, its great density relative to the continents results in *subduction* as plates *converge*.
[As a result, old ocean crust cannot persist, whereas old parts of the buoyant continents can survive for eons.]

(4) The other kind of plate margins, *transforms*, are parallel to the current motion of the plates.

What are the tectonic plates?

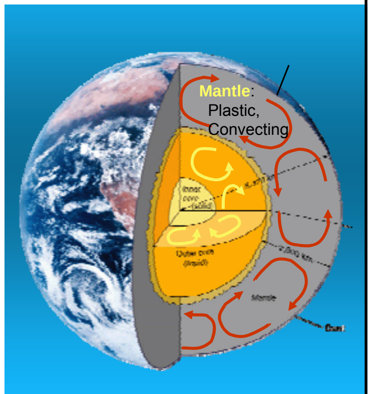


Lithospheric Plates: 100 km thick surface of Earth;

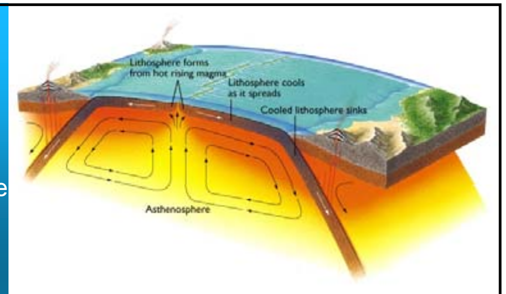
- **Contains crust and upper mantle;**
- **Rigid and brittle - Fractures to produce earthquakes.**

Tectonics and Structural Geology

Tectonic Stresses
resulting from
Internal Energy
(heat driving **convection**)
Deforms the Mantle and Crust
–Bends Rocks, i.e., ductile strain (**Folds**)
–Breaks Rock, i.e., brittle strain (**Joints**) and
–Moves large blocks along **Faults** and
–Releases energy → **Earthquakes**



Tectonic plates are large parts of litosphere 'floating' on the astenosphere



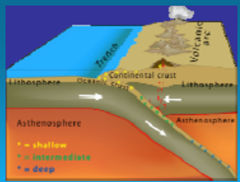
- Convective currents move them around with velocities of several cm/year.
- The plates interact with one another in three basic ways:

1. **They collide**
2. **They move away from each other**
3. **They slide one past another**

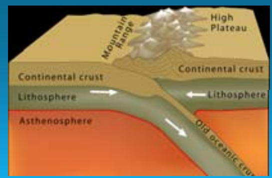
Convergent Plate Boundaries

Ocean /Ocean convergence (Marianas)

Plates push together.
A) The denser plate subducts, or
B) two continental plates crunch together to form high mountains.

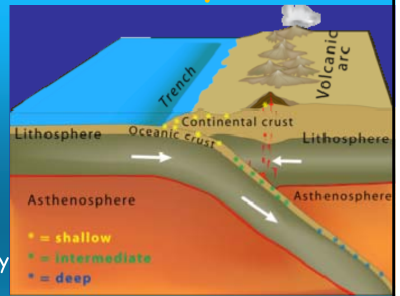


Ocean /Continent convergence (Cascades)



Continent/Continent Collision (Himalayas)

Earthquakes at different depths

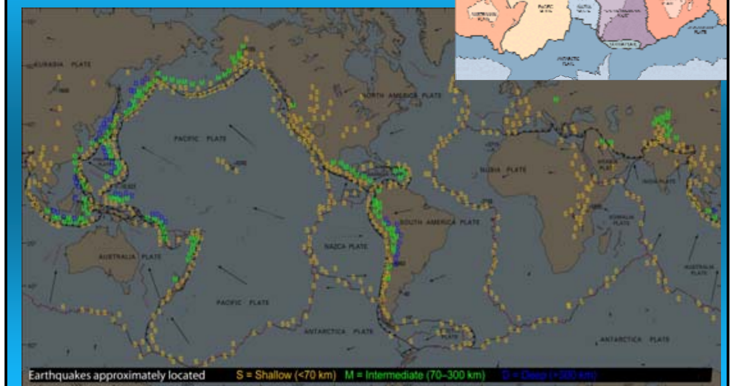


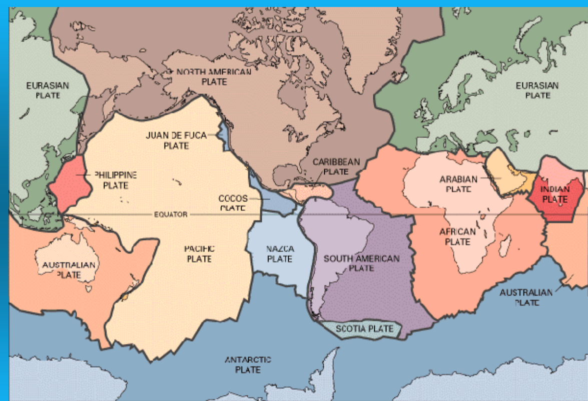
Shallow earthquakes:
The most destructive of these occur *between* the plates *on* the plate boundary.
Shallow earthquakes also occur *within* the subducting plate and *within* the overriding plate near the plate boundary

Intermediate and Deep earthquakes:
The depth range defined as "intermediate" is 100 – 300 km deep while "deep" earthquakes are in the 300 – 700 km depth range.
Intermediate and deep earthquakes occur only *within* the subducting oceanic lithosphere.

World Seismicity & Plat

Earthquake locations coincide wit
and the deepest quakes (blue) are

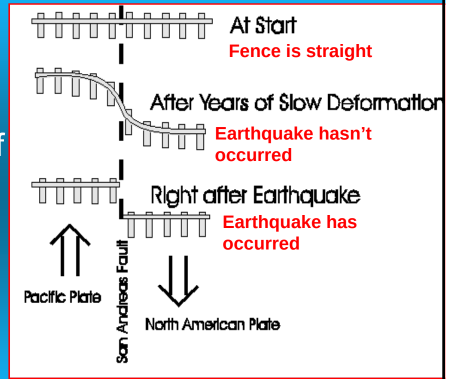




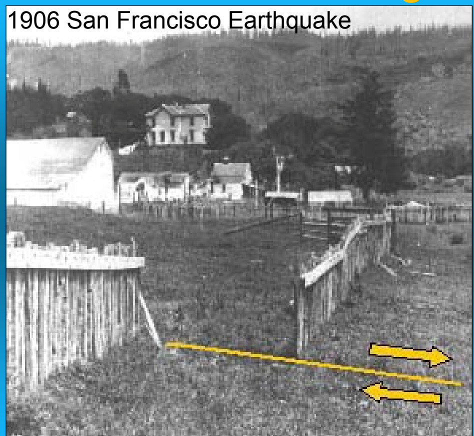
Faults
Earthquake Mechanism

Horizontal Movement along Fault

Fault:
Fracture in the Earth's crust along which two blocks of the crust may suddenly slip with respect to each other during an earthquake



Horizontal Movement along Fault



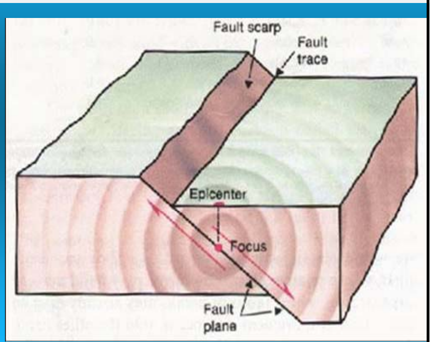
Earthquake Mechanism

An earthquake is caused by a sudden slip on a fault. The tectonic plates are always slowly moving, but they get stuck at their edges due to friction. When the stress on the edge overcomes the friction, there is an earthquake that releases energy in waves that travel through the earth's crust and cause the shaking that we feel.

Earthquake Mechanism

At certain point of stress build-up, sudden slip of rock mass in fault zone causes release of strain energy which propagates through the earth's crust in the form of waves.

- Travelling waves shake the ground which may cause damage
- Earthquakes tend to reoccur along faults, which reflect zones of weakness in the Earth's crust.



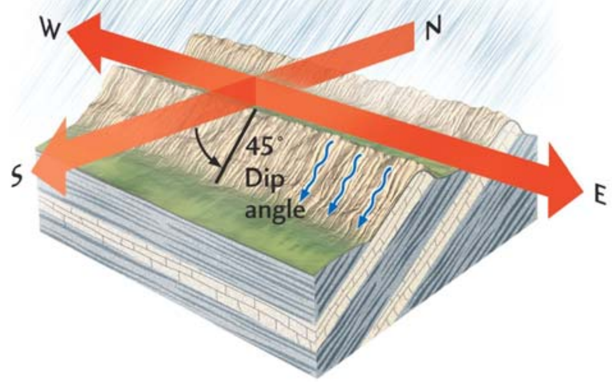
Strike:

Intersection of horizontal plane with dipping surface of stratum (layer).

Dip:

Acute angle between the inclined (dipping) stratum (layer) and the horizontal surface measured perpendicular to the strike direction.

In this figure the strike is in the EW direction and the dip angle is 45°



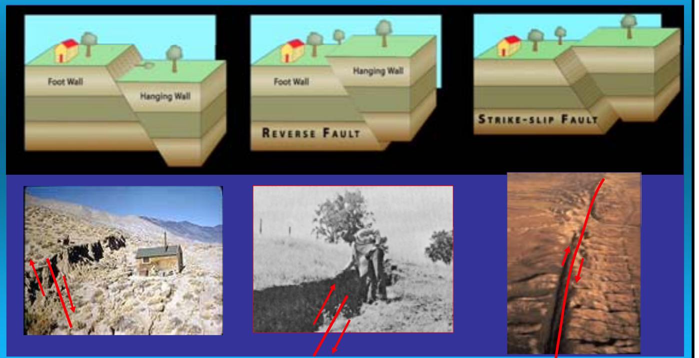
Types of Faults (based on geometry)

- ❖Normal fault
  - – Horst and Grabens
- ❖Reverse fault / Thrust fault
- ❖Strike-Slip fault
  - - Left Lateral & Right Lateral
- ❖Oblique Slip fault

Normal | Reverse | Strike slip

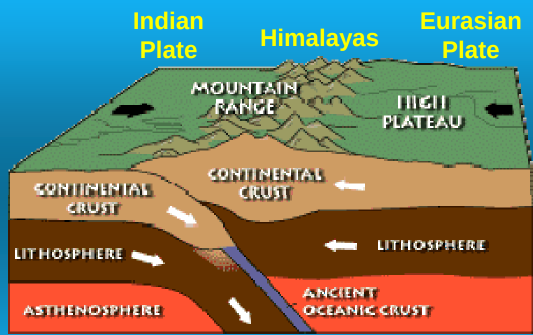
Movement along Dip direction | Horizontal movement

Normal	Reverse	Strike slip
Basin & Range African Rift	Himalayas Rocky Mountains	San Andreas, Calif. N. Anatolian, Turkey

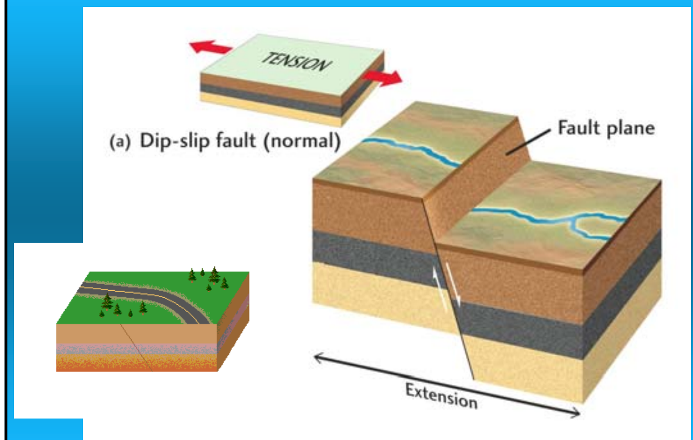


USGS photographs

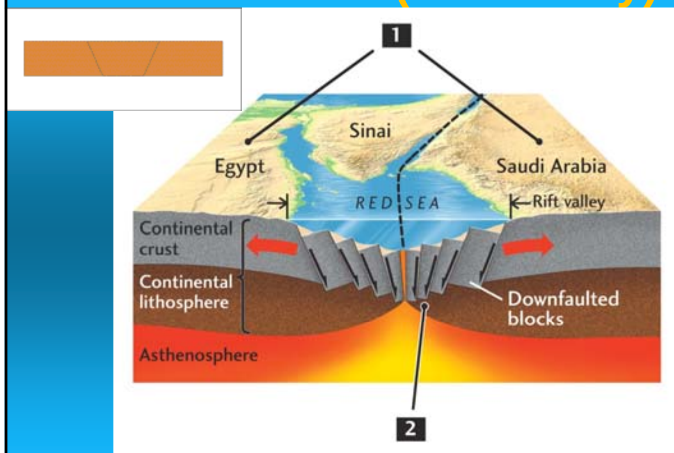
What type of Fault is this ?



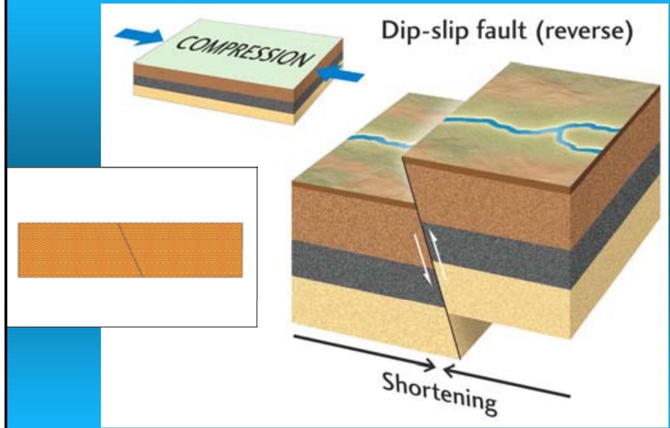
Normal Fault



Normal Fault (Rift Valley)



Reverse Fault



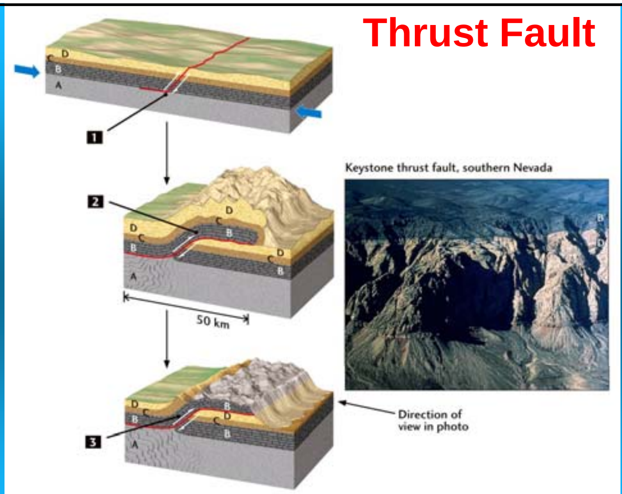
Reverse Fault & Thrust Fault

Reverse fault and Thrust fault is similar in that the hanging wall moves upward relative to footwall.

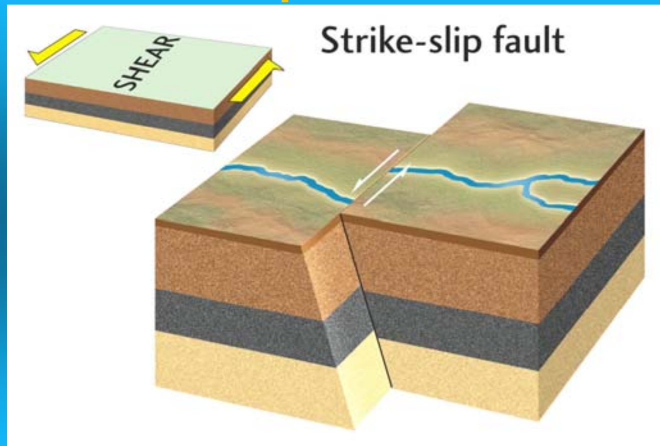
Reverse fault dips more than 45°

Thrust fault dips less than 45°

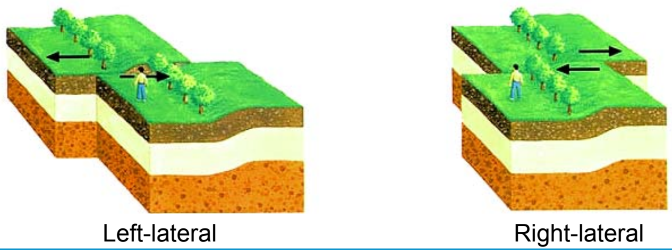
Thrust Fault



Strike-Slip Fault

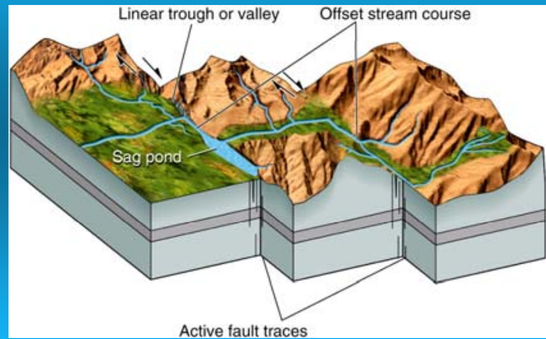


Strike-Slip Fault (contd.)

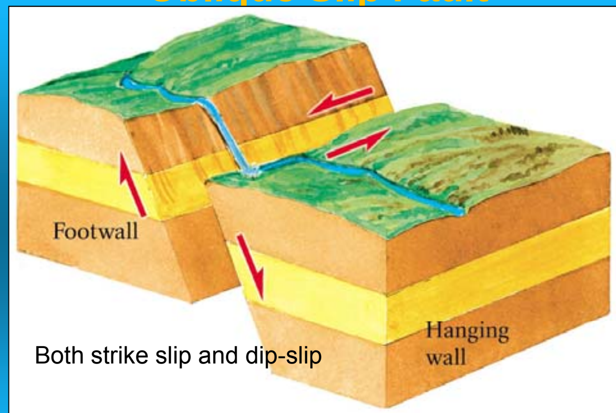


Strike Slip Faults

- Physiographic Features



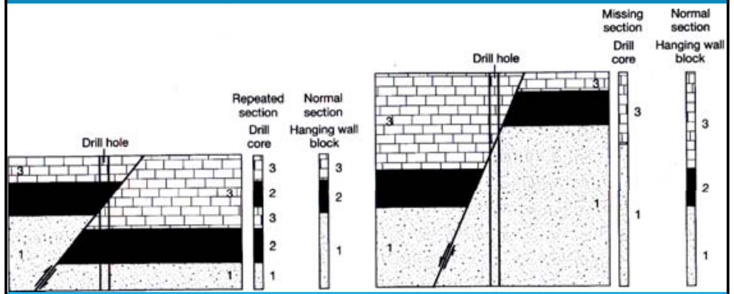
Oblique Slip Fault



Also seen in Transform Faults such as San Andreas

Drilling through a fault

Strata may be
repeated or omitted



Definitions related to Fault

A fault line is the surface trace of a fault, the line of intersection between the fault plane and the Earth's surface.

Faults do not usually consist of a single, clean fracture plane, they consist of fault zones where complex deformation takes place.

The two sides of a non-vertical fault are known as the hanging wall and footwall. The hanging wall occurs above the fault plane and the footwall below the fault.

Fault Zone Structure

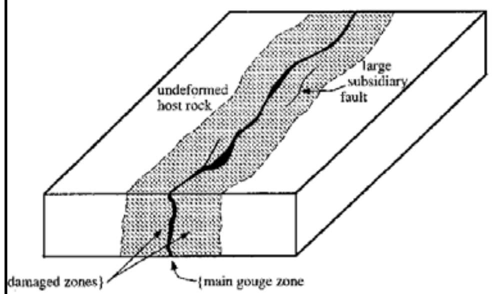
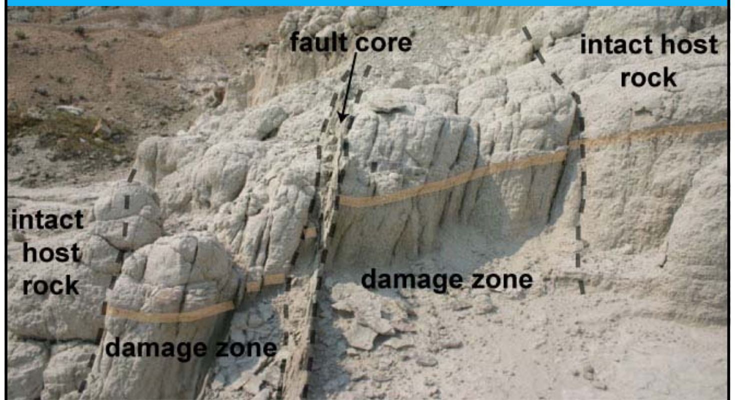


Fig. 1. Fault Zone Structure. Generalized fault zone structure showing main gouge zone along which most fault displacement occurs, surrounded by damaged zones, characterized by subsidiary deformational features (faults, fractures, cataclasis), and surrounding undeformed host rock (after Chester and Logan, 1986).



Recognition of fault

Faults are generally recognized in the field not by direct observations, but by drawing inference from lithological and other physiographical evidences available.

Lithological Evidences:

Slickenslides – rock surface may be polished but containing striations and grooves

Breccias and Gouge – rocks highly fractured into angular fragments called breccias. Sometimes very fine clay like material is present called gouge

Recognition of fault (contd.)

Lithological Evidences:

Shear Zones – presence of closely spaced fractures along which movements have been distributed. Weathering along such zone is more than adjacent rocks.

Dislocation of Strata – Abrupt termination (discontinuation) of bed, fold, dyke etc. along common line or zone. Repeatation or omission of strata. Offset of strata indicating slip.

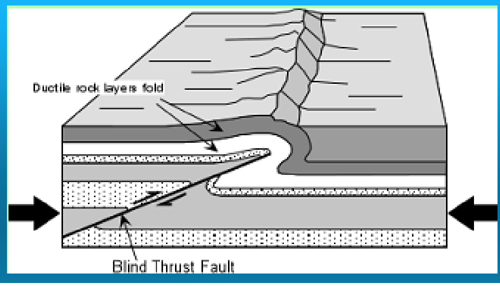
Recognition of fault (contd.)

Physiographical Evidences:

Escarpments – fault scarp, fault-line scarp.

Other topographical evidences– Number of springs arranged in a line. Local deviation of stream from its main course. Offsets of ridges.

Blind Fault



A blind thrust fault is a thrust fault that does not rupture all the way up to the surface so there is no evidence of it on the ground.

Active Fault

An active fault is a fault that is likely to have another earthquake sometime in the future. Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years.

Practical engineering Aspects: Faults

Faulted rocks generally offer unstable sites from engineering considerations, because further fresh movements may take place along the faults at any time in future. Thus, if a structure is constructed on faults, then any future movements along the fault planes may endanger the stability of the structure, and thus causing it to collapse.

Hence, an engineer, as a general rule, must try to avoid locating any major structures on fault. **Earthquake shaking is also very strong and has different characteristics in the vicinity of the fault.**

This is much more necessary to follow in the region where fault(s) have been active in the recent past.

Practical engineering Aspects: Faults

Nevertheless, sometimes, it becomes necessary for an engineer to design and construct even his major structures in moderately faulted regions. In such cases, precautions must be taken to avoid any major failures, either by seismic effects caused by movements along the faults, or due to heavy leakage that may take place through the faulted rocks. The improvement works in faulted rocks, such as excavation of weaker material from the fault zone and refilling or grouting it with cement concrete, etc. may therefore, become neces-sary. The additional safety factors in designs and constructions will have to be adopted.

....

Fault ?

Joints

Difference between Fault and Joint

Joints are fractures, but which do not show clear movement of blocks across them.

Faults are also fractures but with movement of blocks (rock mass) across the fractures

Fractures and Joints

- Joints occur where a rock breaks but there is no displacement or faulting associated with the break. Joints are not singular features, but they occur in sets within a given type or area of a rock.
- Fractures are breaks in rocks that are often singular more random features and are not associated with a set of joints. Fractures often occur in association with faults or folds.
- Crustal movements, deformation, or other tectonic related movements can cause rocks to joint or fracture.
- Joints and fractures form from compression, tension, or shear stress and can range in size from millimeters to kilometers.

Fractures and Joints (contd.)

- Common forms of jointing are columnar, sheet jointing, and tensional joints.
- Columnar jointing occurs when igneous rocks cool and develop shrinkage joints along pillar-like columns.
- Sheeting joints occur when the layers of rock release pressure and exfoliate along parallel planes.
- Brittle fractures and tensional joints are caused by regionally extensive compressional or elongated pressures along folds in the crustal rocks.
- Sometimes, jointing is obvious, but the processes that caused it may be unknown, or difficult to identify.
- Fractures and joints create a variety of pathways for water to flow through, which weaken the rock and facilitate chemical, biological, and mechanical weathering processes.

Joints: Fractures – with no movement

Standard: 3-3.6, 3-3.8
Standard: 8-3.7, 8-3.9

Jointing

Copyright Larry Fellows, Arizona Geological Survey

These two images are an example of columnar jointing. The image on the top is a side view and the image below is from the top. These hexagonal columns of rock formed from cooled basalt are part of Devil's Postpile National Monument in California.

The image below is of vertical jointed, bedded meta-sandstone in the Snake Range in Nevada.

Copyright © Bruce Molnia, USGS

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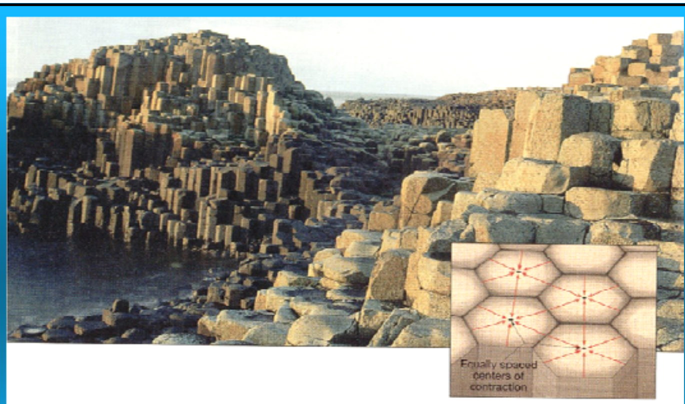


CONTRACTION JOINTS IN VOLCANIC ROCK. COOLING LAVA CONTRACTS AND FORMS HEXAGONAL FRACTURES (COLUMNAR JOINTING)

Practical engineering Aspects: Joints

For construction of any major civil engineering structure in any area, it is absolutely necessary to investigate the rock joints thoroughly, mainly because joints act as sources of weakness for the rocks, and also as sources of leakage through the rocks.

Hence, if the proposed foundation rocks for a dam or a reservoir happens to be heavily jointed, and if the water-table of the region is low, then the leakage from the reservoir to the underground may be very heavy, finally resulting in abandoning the proposed site.

Practical engineering Aspects: Joints

Similarly, in construction of tunnels, if the roof or the side rocks, are highly fractured or jointed, the ground water may seep into the tunnel, thus creating acute water troubles, in addition to its becoming unstable or unsafe structurally.

The joints in rocks play a very important role in landslides in hilly regions, because they may serve as slip surfaces. For example, joints dipping towards the hill slope may allow the overlying, unsupported mass of rock to slide down, causing a landslide. Hence, the occurrence and orientation of joints, and their possibilities of lubrications, must be investigated, as they may lead to landslides from under the highway, or along the proposed engineering structure

Earthquake Magnitude

(Represents Earthquake Energy)

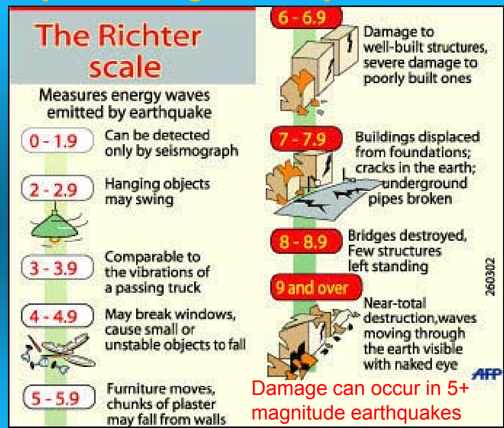
There are different magnitude scales

Earthquake Magnitude (M)

Reflects amount of energy released in an earthquake.

Description	Magnitude	Number of events per year
Great	8 and higher	1
Major	7 - 7.9	17
Strong	6 - 6.9	134
Moderate	5 - 5.9	1319
Light	4 - 4.9	13,000 (estimated)
Minor	3 - 3.9	130,000 (estimated)
Very Minor	2 - 2.9	1,300,000 (estimated)

Earthquake Magnitude (Richter Scale)



Magnitude (M) of an earthquake is a measure of the size of an earthquake based on the total amount of the energy released by an earthquake, when the over-strained rocks suddenly rebound to cause the given earthquake. The released energy, infact, travels in the form of earthquake waves, which are recorded at the receiving station (seismograph station). The energy released (E) and the earthquake magnitude (M) are estimated with the help of the record of the surface waves, as discussed below:
A typical accelerogram of earthquake waves produced at a seismographic observatory is shown in Fig. 6.14. Such a graph will indicate the maximum acceleration (ex) reached during the earthquake (maximum ordinate recorded on Y-axis). This value of maximum ground acceleration (ex) is then empirically connected to estimate the value of E i.e. max. energy released, by the equation:

The magnitude (M) of an earthquake has also been connected by Richter with the max. displacement amplitude (A) of the recorded surface waves, by the equation :

$$M = \log_{10} A - \log_{10} A_0 \qquad ...(6.3)$$

where M = Magnitude in Richter

A = Max. Trace amplitude in mm (Fig. 6.8)

A_0 = Distance correction (Fig. 6.15) for the known (estimated) value of distance D of the observatory (recording station) from the epicentre of the earthquake.

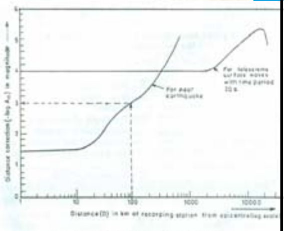


Fig. 6.15. Estimating Distance Correction (A_0).

Say for example, if the max. *trace amplitude* on the seismograph is measured to be 10 mm, and the distance of the epicentre from the seismographic station is estimated to be 100 km (say), then from Fig. 6.15, we read for 100 km, the value of (–) $\log_{10} A_0 = 3$

$$\therefore \quad M = \log_{10} 10 + 3$$
$$= 1 + 3 = 4.0 \text{ Richter.}$$

The Richter's scale of magnitude in fact, classifies the various shocks in magnitude varying from 1 to 10, and its every successive higher number represents a little over 30 fold *(i.e. $10^{1.5} \approx 30$) increase* in energy released (Please see Eq. 6.2). Thus, an earthquake of magnitude 9 has over 30 times more energy than an earthquake of magnitude 8, and 900 times more energy than an earthquake of magnitude 7, and 27000 times more energy than an earthquake of magnitude 6. The complete scale is given in table 6.4.

Table 6.4. Richter's Scale of Magnitude

Magnitude Number	*App. Energy released in Joules (Computed by Eq. 6.1)*	*Approximate Amount of TNT* explosive required to produce the same energy*	*Effects of energy released*
(1)	(2)	(3)	(4)
0	$10^{4.8}$	600 gm	A small explosion to uproot a stem of a tree.
1	$10^{6.3}$	20 kg	An explosive used in foundation excavation for construction.
2	$10^{7.8}$	600 kg	A normal explosion in stone quarry
3	$10^{9.3}$	20,000 kg (*i.e.* 20 t)	A big explosion in an open cast mine
4	$10^{10.8}$	600 t	The first explosion of the experimental atom bomb

*producing about 100 kJ/kg.

Magnitude Number	App. Energy released in Joules (Computed by Eq. 6.1)	Approximate Amount of TNT* explosive required to produce the same energy	Effects of energy released
5	$10^{12.3} = x$	20,000 t	Atom bomb exploded at Hiroshima
6	$10^{13.8} \approx 30x$	600,000 t (0.6 Mt)	An explosion of hydrogen bomb
7	$10^{15.3} \approx 900x$	20 Mt	Simultaneous explosion of 30 hydrogen bombs
8	$10^{16.8} \approx 27000x$	600 Mt	About 1000 hydrogen bombs exploding simultaneously
9	$10^{18.3} \approx 810000x$	20,000 Mt	Simultaneous explosion of 30,000 hydrogen bombs. Energy equivalent of borning 5 yrs. production of coal and oil in the entire world.

Rupture Length

San Andreas fault

1906 San Francisco EQ
M7.7-7.9
Rupture L =470 km

1989 Loma Prieta EQ
M7.0
Rupture L = 40 km [37]

Earthquake Intensity

Modified Mercalli Intensity Scale

It measures the impact of an earthquake at different places by sending out trained observers to look at the damage done to the built environment and the earth (landslides etc.) and at the reaction of people to the event.

EARTHQUAKE INTENSITY

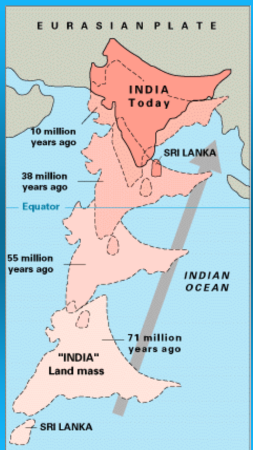
Intensity	Accleration produced (mm/sec²)	Name of the shock and its effect
I	Less than 10	Instrumental- recorded only by the seismograph
II	Over 10	Feeble-felt only by some very sensitive people
III	Over 25	Slight-commonly felt by people
IV	Over 50	Moderate-commonly felt by people
V	Over 100	Fairly strong-considerable amount of vibration which wakes up people at sleep and causes ringing bells
VI	Over 250	Strong-minor damage to the buildings, particu- larly to their over hanging and projecting parts.
VII	Over 500	very strong-damage to the buildings, such as cracks in the walls etc.
VIII	Over 1000	Destructive-greater damage to the buildings involving over througing of overhanging and projecting portions like chimnets.
IX	Over 2500	Ruinous- sever damage to the buildings, involving their over througing
X	Over 5000	Disasterous-with a sever, general destruction of buildings
XI	Over 7500	Very disasterous-sever destruction of buildings and cracking of the ground.
XII	Over 9800	Catastrohpc-large scale to complete destruction of the buildings and ground.

An earthquake has one magnitude, however it may vary by small amount depending on which magnitude scale you are using. Energy is a measure of magnitude.

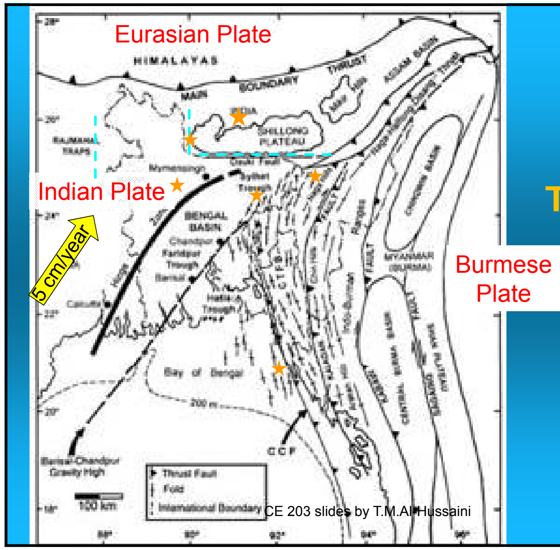
On the other hand, the **earthquake has different intensities at different locations**, usually intensity decreases with distance. Ground acceleration is a measure of intensity at a particular place.

Seismicity in and around Bangladesh

Plate Movement - Bangladesh case



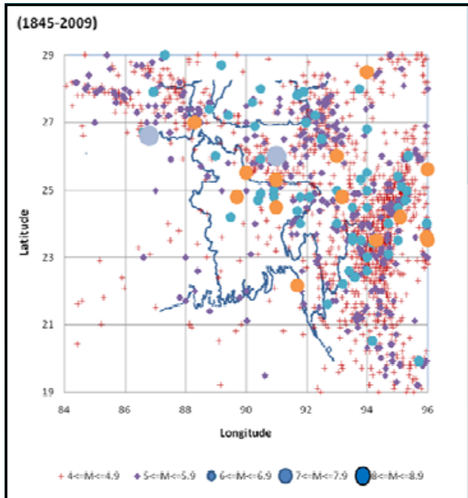
Tectonic Map of Bengal Basin



Strong Earthquakes affecting Bangladesh

Date	Earthquake	Magnitude	Distance (km) from Dhaka
2nd April, 1762	Chittagong Earthquake	7.5	260+
10 Jan, 1869	Cachar Earthquake	7.5	250
14 July, 1885	Bengal Earthquake	7.0	170
12 June, 1897	Great Indian Earthquake	8.1 (revised)	230
8 July, 1918	Srimongal Earthquake	7.6	150
3 July, 1930	Dhubri Earthquake	7.1	250

No large earthquake in last 80+ years!



EARTHQUAKES IN & AROUND BANGLADESH

New Earthquake Catalogue formed covering 1845-2009

Damage due to Recent Earthquakes


1997: RC Frame Building, Chittagong


2003: Brick Masonry Building, Kolabunia


2003: Long crack along River, Kolabunia

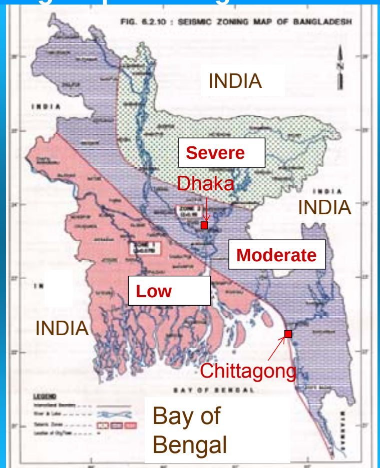

2003: Mud-walled House, Kolabunia

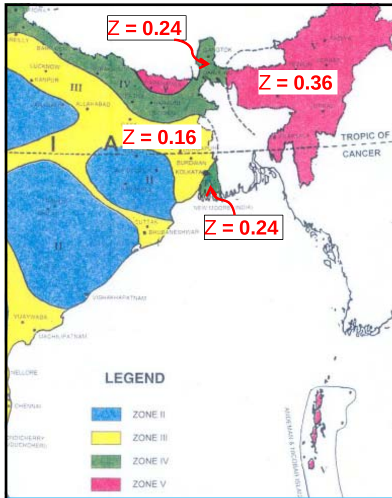
Seismicity Hazard Map of Bangladesh

Seismic Zoning Map of Bangladesh

Bangladesh National Building Code (1993)

Bangladesh is divided into 3 zones based on intensity of ground shaking:
(i) Severe
(ii) Moderate
(iii) Low

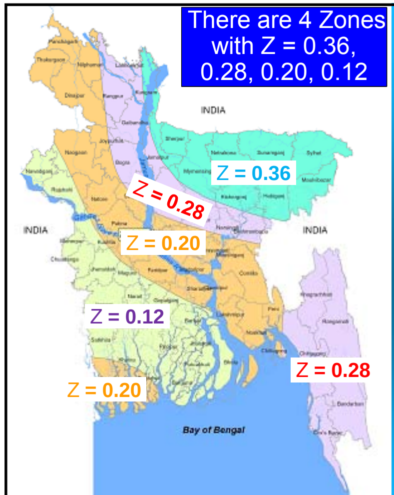




SEISMIC ZONING MAP OF INDIA, BUILDING CODE (2005)

Z represents the maximum considered earthquake (MCE) ground acceleration (g) in these zones.

Note that there are three zone factors surrounding Bangladesh:
0.36, 0.28 and 0.16.

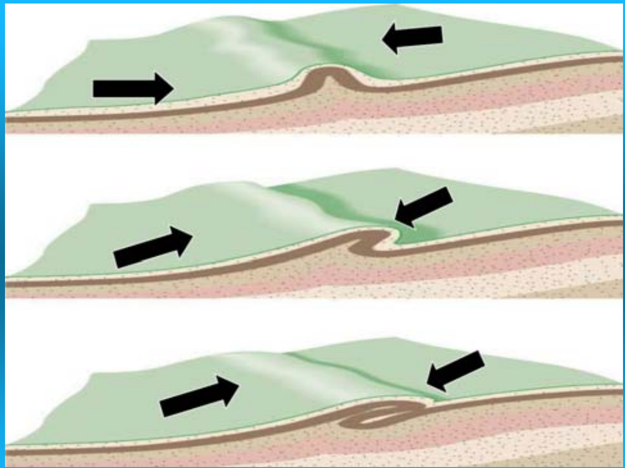


PROPOSED SEISMIC ZONING MAP (2010)

Al-Hussaini et al., 2012

Z represents the **maximum considered earthquake (MCE) ground acceleration (g)** in these zones.

Folds



Causes of Folding

Tectonic Causes:

- Compressive stress developed in the earths crust
- Igneous intrusions – magma intrusion from beneath may result in folding of overlying strata.
- Salt intrusions

Non-Tectonic Causes (mainly due to gravitational forces):

- Landslide
- Creep – along hill slopes
- Isostatic setting – bending of wide basin due to increased sediment load in the middle.
- Subsidence into solution cavities
- Glacier movement induced stresses

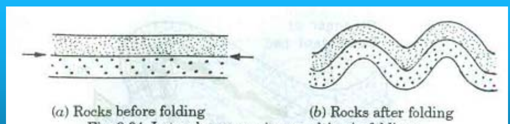


Fig. 8.34. Lateral compression resulting in folding.

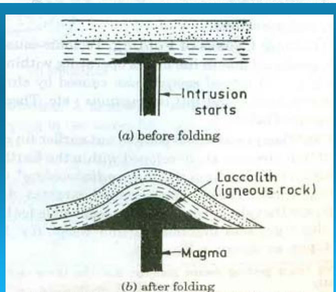


Fig. 8.36. Folding due to intrusion of magma.

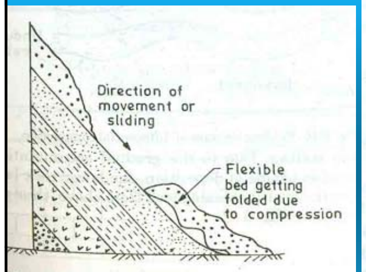


Fig. 8.38. Folding of a flexible bed by landsliding.

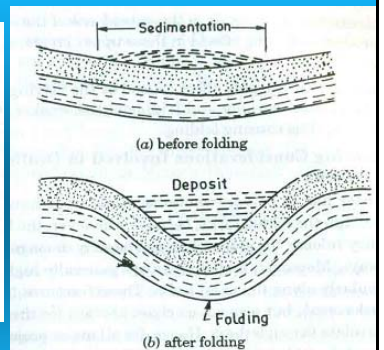
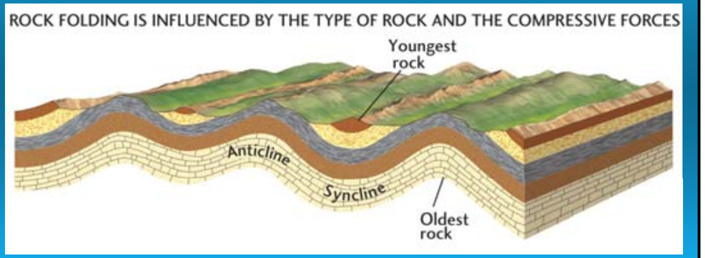


Fig. 8.41. Folding due to isostatic settling.

Folding of Rocks

- Produced by compressive forces

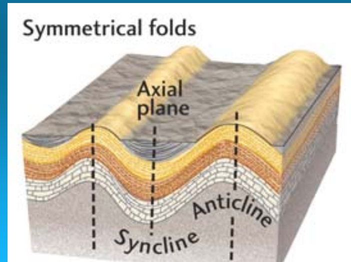


CE 203 slides by T.M.Al-Hussaini 411

syncline: a sequence of folded rocks with the youngest rocks on the inside of the fold

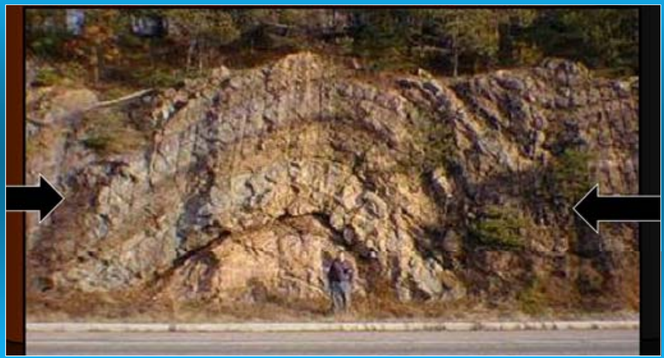
anticline: a sequence of folded rocks with the oldest rocks on the inside of the fold

axial plane: the plane of mirror symmetry dividing the fold into two limbs



CE 203 slides by T.M.Al-Hussaini 412

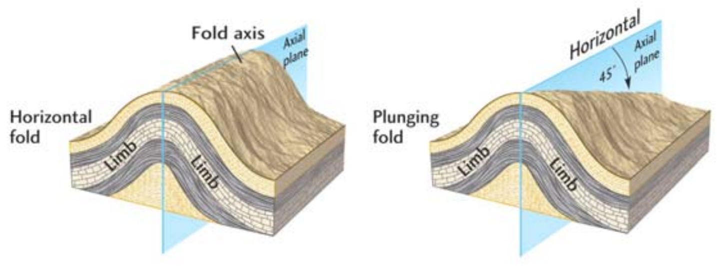
FOLDING CAUSED BY COMPRESSION



CE 203 slides by T.M.Al-Hussaini 413

CE 203 slides by T.M.Al-Hussaini 414

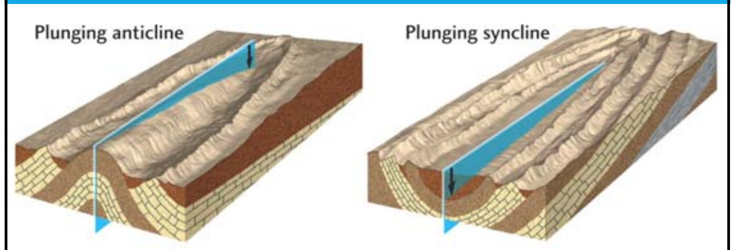
Fig. 10-CO, p. 216



axis: the line formed by the intersection of the axial plane and a bedding plane

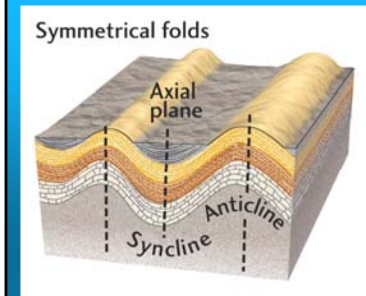
horizontal fold: axis is horizontal

plunging fold: axis is not horizontal

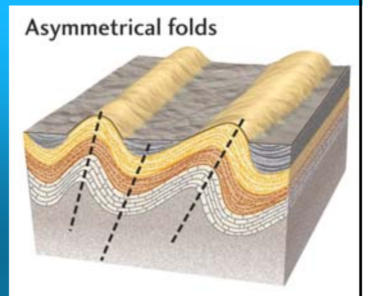


Types of Folds
(based on geometry)

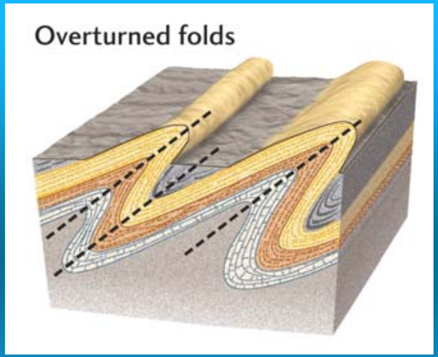
- **Symmetrical folds**
- **Asymmetrical folds**
- **Overturned folds**
- **Recumbent folds**



Beds dip away symmetrically from the axial plane

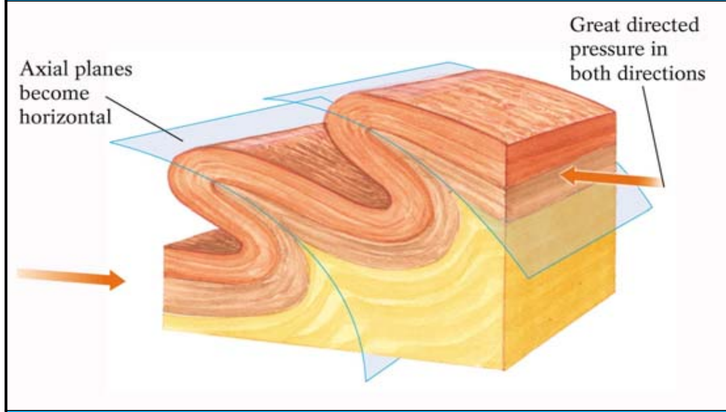


Beds on one side of the axial plane dip steeper than those on the other side



Both limbs dip in
the same direction

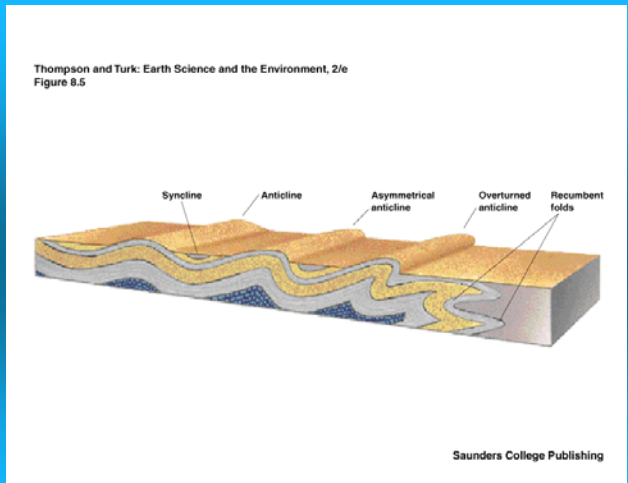
Recumbent Fold



Types of Fold (Contd.)

- **Symmetrical folds:** Limbs dipping symmetrically on each side of axial plane. Axial plane is vertical.
- **Asymmetrical folds:** have the bed on one side of fold dipping more steeply than other. Axial plane is not vertical.
- **Overturned folds:** Both limbs dipping in the same direction.
- **Recumbent folds:** Overturned fold where the axial plane is almost horizontal.

Fig. Story 11.16



Practical engineering Aspects: Folds

A civil engineer has to be very cautious, while he is handling or excavating through the folded rocks, because whenever, the folds are disturbed, they release the stored energy and may damage the site in various ways. Moreover, folded rocks are generally highly fractured, particularly along the axial parts. These fractures, not only make the rocks weak, but also act as channel-ways for the surface waters to percolate through them. Hence, for all major projects, like construction of tunnels, site selection for dams and reservoirs,
construction of highways, etc. due consideration must be given to the presence of folds.

Practical engineering Aspects: Folds

(i) Synclinal folded rocks may yield hard and tough quality stones; whereas, anticlinal folded rocks will yield weaker stones.

(ii) Folded rocks are under considerable strain, and hence, excavations through them may be accompanied by slips and rock bursts.

(iii) Folded rocks are generally shattered and weak, particularly in the axial regions; and hence, they are unsafe to be trusted as roofs or floors of tunnels, or as foundations for dams. Such regions should therefore, be avoided for such purposes, or must be thoroughly investigated, and remedial measures taken, if at all adopted for such uses.

Practical engineering Aspects: Folds

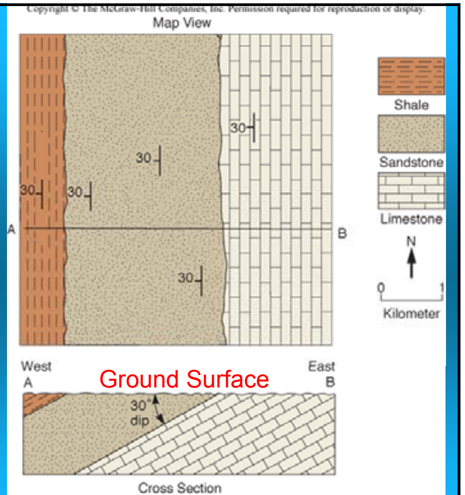
(iv) Fractured folded rocks are highly permeable, and as such may pose numerous problems. Say for example, while excavating tunnels through such regions, ground water may rush into the excavation. Similarly, in dam construction in such areas, heavy leakage from beneath the dam may take place.

(v) Since the folded rocks offer great prospects for ground water, they become quite important for engineers searching for water supplies. Infact, artesian conditions are developed only when aquifers are folded (or inclined) as synclines, and are enclosed between top and bottom impervious layers.

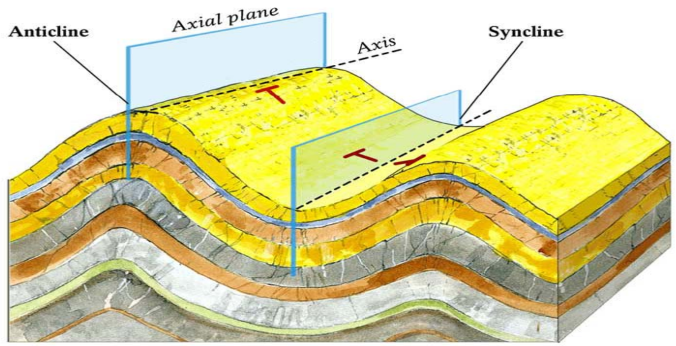
(vi) The anticlinal folds provide good prospects for stored petroleum.

Rock Outcrop

Outcrops are places where bedrock is exposed at the ground surface

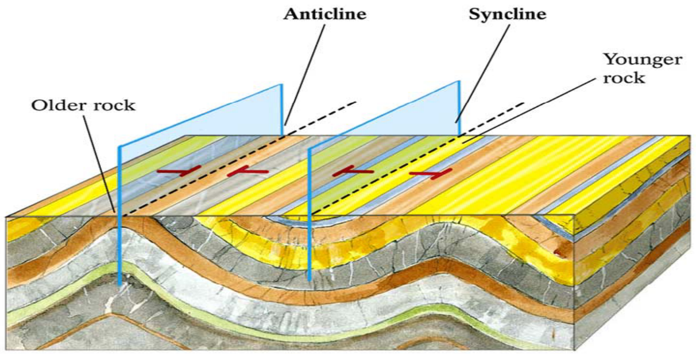


Folded Rock Before Erosion



1 Folded rocks before erosion

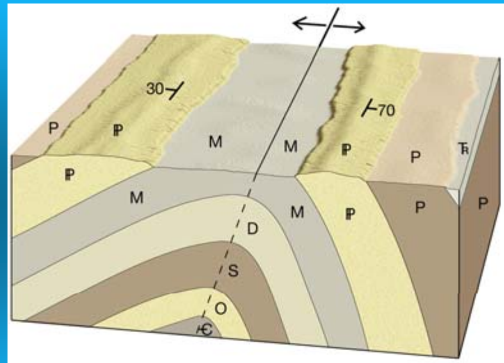
Folded Rock After Erosion



2 After erosion

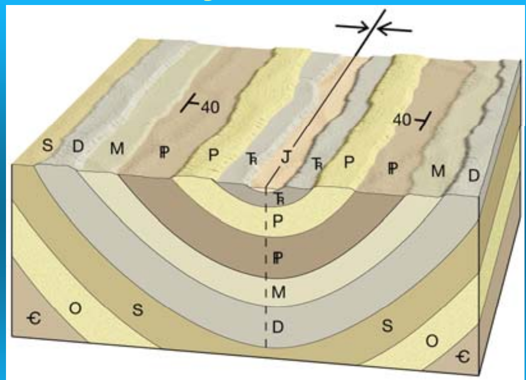
Eroded Anticline, older rocks in center.
Syncline is opposite.

Anticline



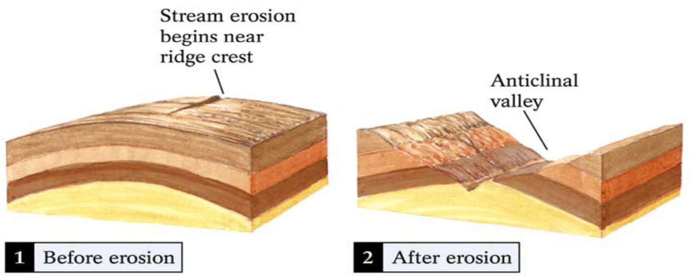
A. Anticline (asymmetrical): oldest rocks (Є) occur in the center of the fold

Syncline



B. Syncline (symmetrical): youngest rocks (J) occur in the center of the fold

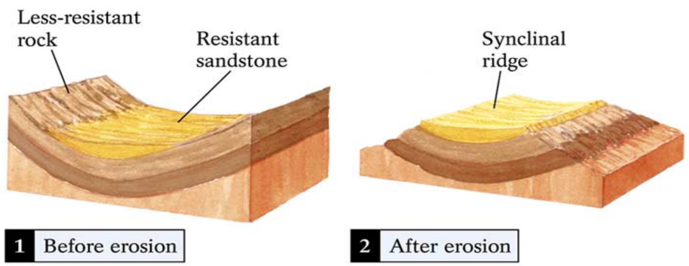
Topography may be opposite of Structure Anticline Before/After Erosion



(a) Anticline with highly erodible surface

Notice center rock oldest

Topography may be opposite of Structure Syncline Before/After Erosion

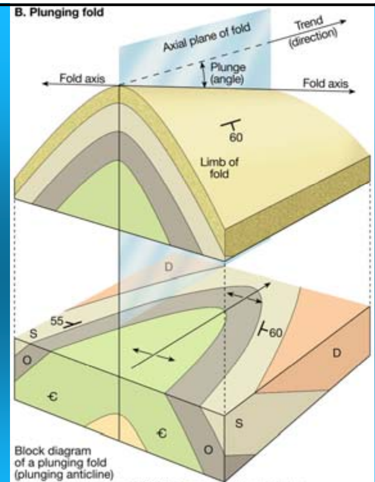


(b) Syncline with resistant rock at axis

Notice center rock youngest

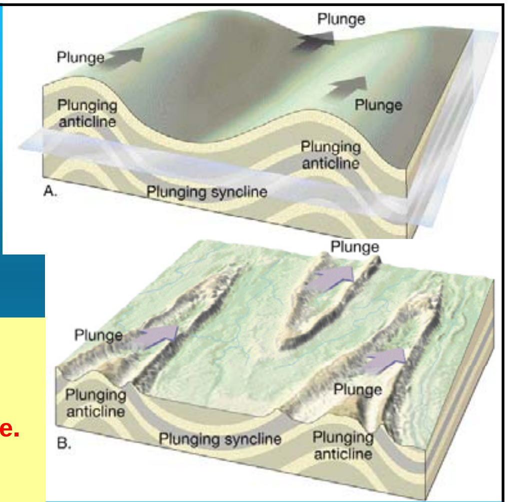
Plunging Anticline

Where surfaces have been leveled by erosion, plunging folds form V- or horseshoe-shaped patterns of exposed rock layers (beds).

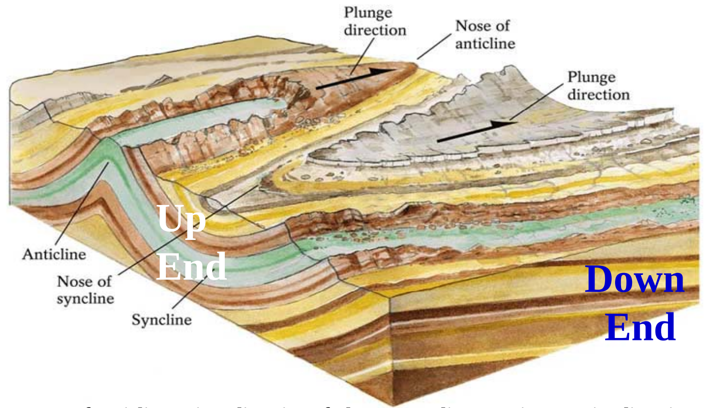


"the law of v's" gives the direction of dip and some indication of the dip angle (the longer the V, the lower the angle of dip).

For anticline, the direction of V coincides with direction of plunge. For syncline the opposite occurs.

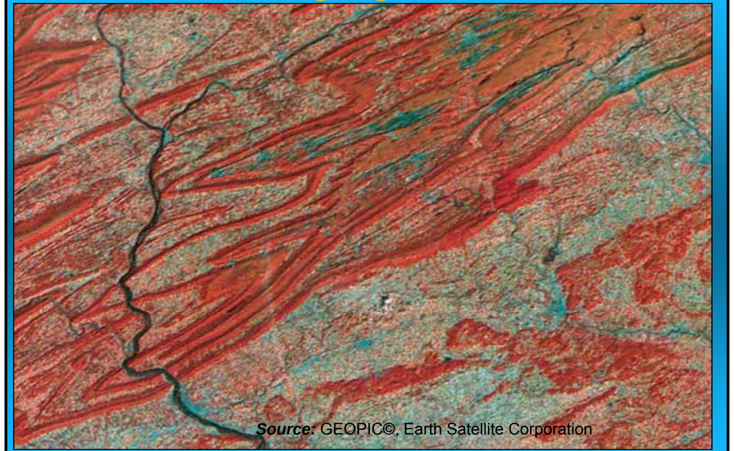


Plunging Folds

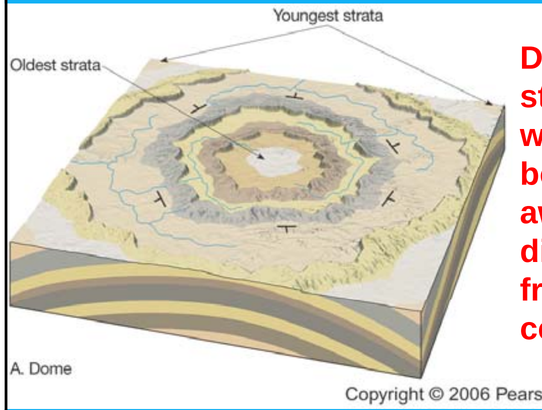


Nose of anticline points direction of plunge, syncline nose in opposite direction

Plunging Folds

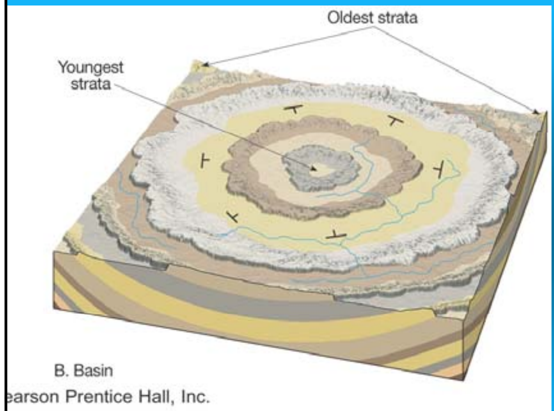


Dome



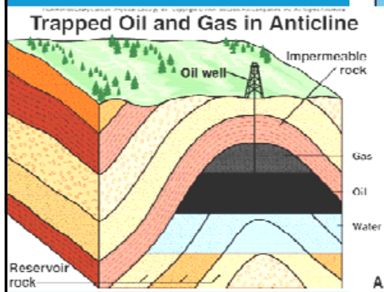
Domes are structures in which the beds dip away in all directions from a central point.

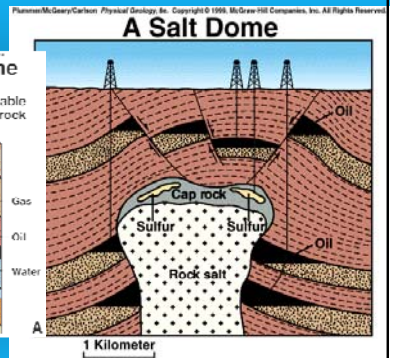
Basin



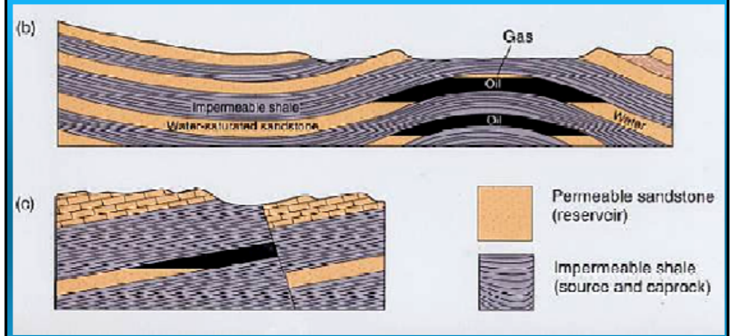
Basins are structures in which the beds dip toward a central point.

Oil Reservoirs



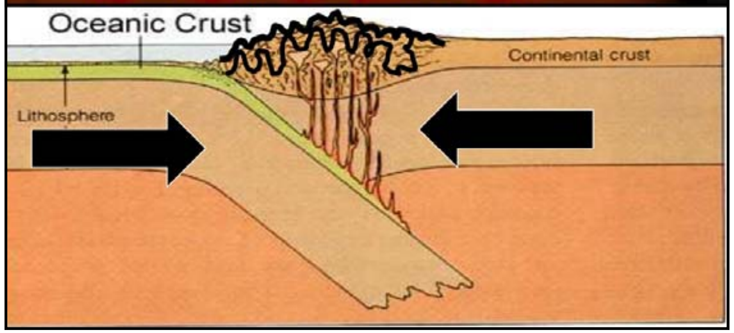


Oil Reservoirs (contd.)

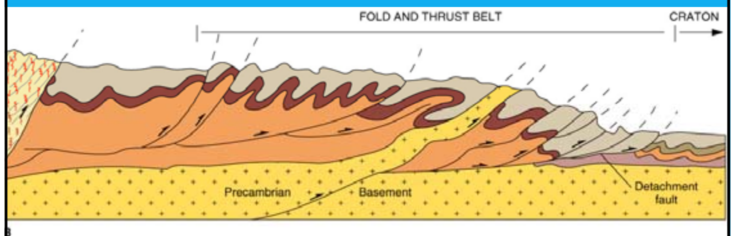


Orogeny

- Orogeny: The formation of mountain ranges by intense upward displacement of the earth's crust.
  - Usually associated with folding, thrust faulting, and other compressional processes.



Folds & Thrust Faults

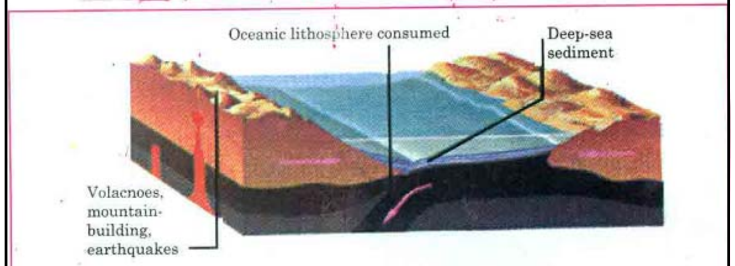


Orogeny (contd.)

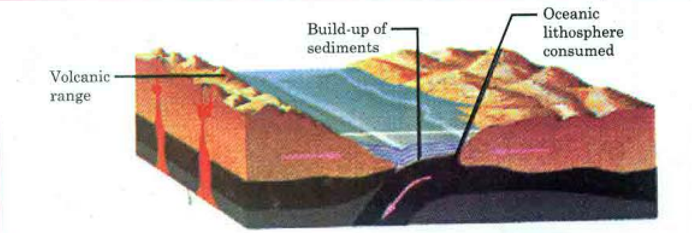
The processes of orogeny can take tens of millions of years and build mountains from plains or the ocean floor. Frequently, rock formations that undergo orogeny are severely deformed and undergo metamorphism. During orogeny, deeply buried rocks may be pushed to the surface. Sea bottom and near shore material may cover some or all of the orogenic area.

Continent-Continent Collision

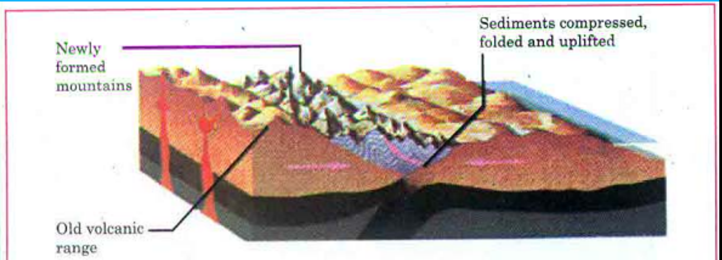
Colour Photo Fig. 6.8. When Continents Collide



When continental blocks move together ocean plate between is destroyed as it slides beneath the continental plate to form a trench. Earthquakes, volcanoes and mountain-building occur on the land.



Sediments are scrapped off the ocean floor by the continental plate and build-up thickly. Sediments on the continental margin are also compressed and raised. Oceanic plate continues to be consumed.



When the ocean floor has been completly consumed, the landmasses collide. Accumulated sediments are compressed, folded and uplifted to form mountain ranges. Older volcanic ranges are also compressed and raised.

Fig. showing Collision of Continents. leading to Earthquakes, Volcanoes, and Building of Mountains.

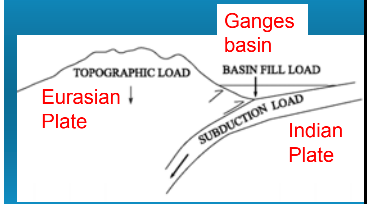
Formation of Himalayas

If the orogeny is due to two continents colliding, the resulting mountains can be very high (Himalayas).

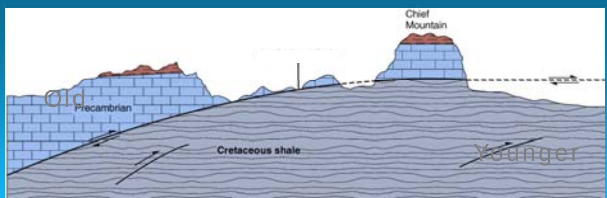
Lifted by the collision of the Indian tectonic plate with the Eurasian Plate, the Himalayan range runs, west-northwest to east-southeast, in an arc 2,400 kilometres (1,500 mi) long.

Formation of Ganges Basin

Basin (such as Ganges basin) may develop adjacent and parallel to a mountain belt, on the plate that is subducted or underthrust during plate collision. Basin receives sediment that is eroded off the adjacent mountain belt, filling with thick sedimentary successions.



Thrust Fault: Glacier NP, Montana



- *Geologic structures* are dynamically-produced patterns or arrangements of rock or sediment that result from forces within the Earth. Such structures are produced as rocks change shape and orientation in response to applied stress. These structures give information about forces within the Earth. Tilted beds, rock outcrops, folds, faults, joints are example of geologic structures.

- *Structural geology* is the study of the shapes, arrangement, and interrelationships of rock units and the forces that cause them. It studies crustal deformation.

Types of Mountains

6.21.1. Volcanic Mountains. As we know by now, volcanoes at various places, throw lavas, which get deposited and solidified in the form of huge conical heaps of solid material around the point of erruption. These huge dome-shaped heaps, when become quite prominent in comparison to the level of the surrounding land, may be called as *volcanic mountains.* Volcanic mountains are generally small or medium sized mountains.

'Mount Vesuvius', 'Agung', and 'Etna' are a few examples of this type of mountains.

Mt. Fuji, Japan

6.21.2. Residual Mountains. The mountains which are formed by the prolonged action of differential-erosion (caused by various erosion agents) acting on the pre-existing plateaus or plains, are called *residual mountains.* Infact, due to differential erosion, the weaker and the less resistant rocks are worn down and lowered, while hard and more resistant rocks remain standing above the ground surface, making hills and hillocks, called residual mountains.

Most of the medium-sized Indian mountains including the 'Vindhyas', the 'Satpuras', the Eastern and the Western 'Ghats', but excluding the 'Himalayas' and the 'Aravallis' all belong to this category.

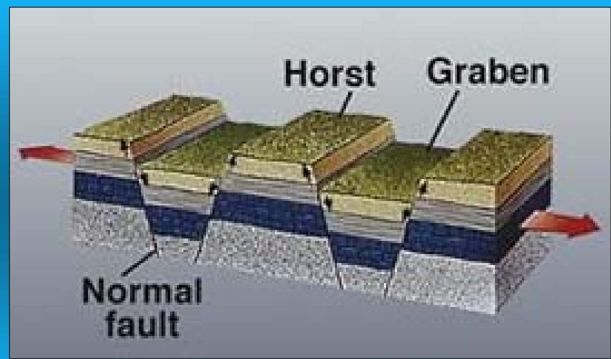
6.21.3. Fault Mountains or Block Mountains. *Faulting* in crustal rocks always result in displacement of the blocks along the rupture plane. Sometimes, this displacement is *lateral*, and at other times, it is *vertical* or *oblique*. During such vertical or oblique motions along fault planes, sometimes, a central block of considerable area may be *thrown up* with respect to the side blocks. This happens when the rock-block, in consideration, has a fault plane on either side, as shown in Fig. 6.22. Such upthrown blocks are termed as *Horsts* ; and when they are of considerable height and size, may be called as *fault mountains*.

Fault-block mountains

- **Rift Valleys, Mid Ocean Ridges**
- Normal Fault Blocks as in East Africa or Western USA

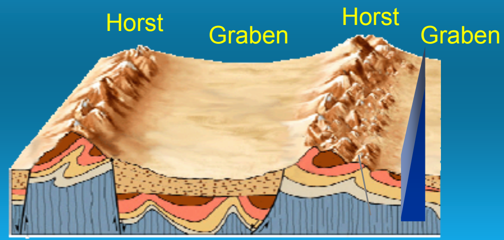
Horst & Grabens (Nevada, USA)

- Horst and graben topography is generated by normal faulting associated with crustal extension.
- The central block termed graben is bounded by normal faults and the graben drops as the crust separates.
- The graben forms an elongated valley that is bound by uplifted ridge-like mountainous structures referred to as horsts.
- Some horsts may tilt slightly producing asymmetric, tilted terrane or mountain ranges.
- In Western USA, horst and graben fault sequences are described as “Basin and Range” topography.

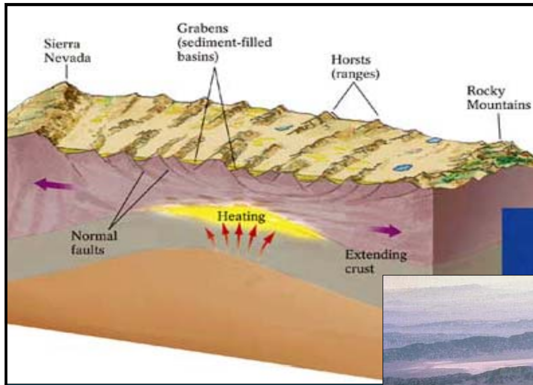


Horsts and Grabens

- Older Rocks are exposed along the ridges formed by the horsts
- Younger rocks lie beneath the grabens
- Sediment fills in the linear valleys



Horst & Grabens (Nevada, USA)



6.21.4. Fold Mountains. Fold mountains are the important mountains of the world, and include the Himalayas and the Alps. They are the most complex in character, possessing all sorts of structural complications in their constitution. These mountains are thus made of rocks, which are generally *jointed, folded* and *faulted*. The formation of these mountains is not very well understood. It is thought that these mountains are formed as a result of certain forces which originate within the Earths' crust, and are called *orogenic** forces; the process of formation being termed as *orogeny*. The Earth movements, which involve folding, faulting and thrusting, are called *orogenic movements*, and involve both horizontal as well as vertical crustal movements. Their formation and alteration over time is reflected in **Coloured Fig. 6.5.**

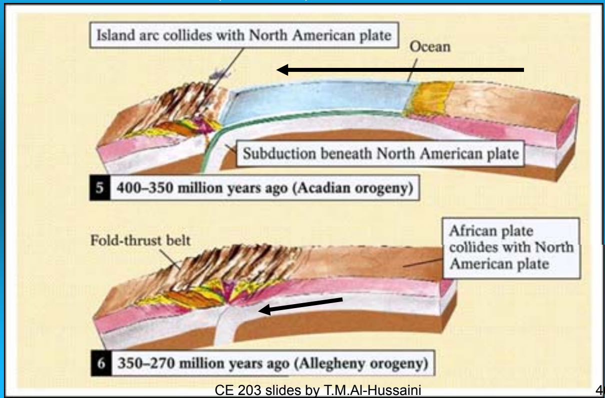
This *orogeny* or *mountain building activity* is a very complex and a time consuming process. Its completion may take millions of years.

Appalachian Mountains

- The Appalachian Mountains extend along the eastern margin of North America from Alabama to Maine in the United States, and through the southeastern provinces of Canada to Newfoundland.
- The Appalachian Mountains were formed during the Paleozoic Era from several orogenic episodes, the Taconic Orogeny (Ordovician ~480 mya), followed by the Acadian Orogeny (Devonian ~400 mya), and lastly the Alleghany Orogeny (Permian ~ 300 mya).
- Each of these major orogenic episodes involved multiple events of folding, faulting, metamorphism, emplacements of igneous intrusions, and uplift.

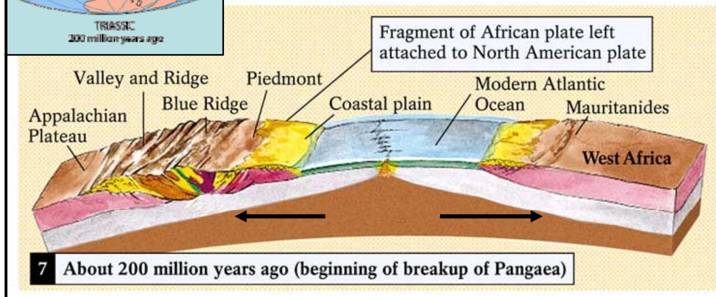
Model for the Evolution of the Southern Appalachians

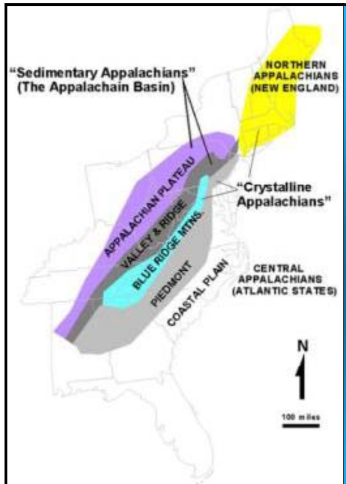
African Plate subducts (westward) underneath North American Plate



Evolution of the Southern Appalachians (cont'd)

Rifting starts (North American Plate moves away from African Plate)





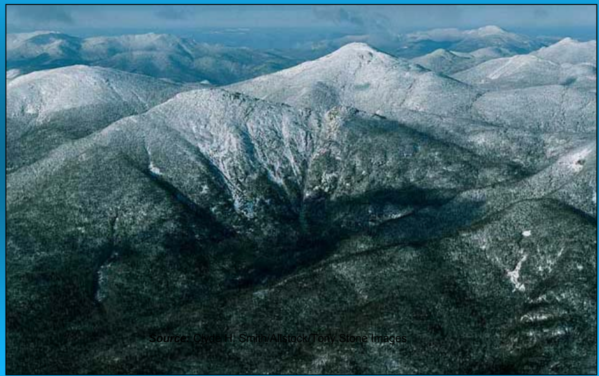
The Appalachian Mountains are divided into four major provinces: Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau.

Photo courtesy of SCGS, SCDNR

Upwarped mountains

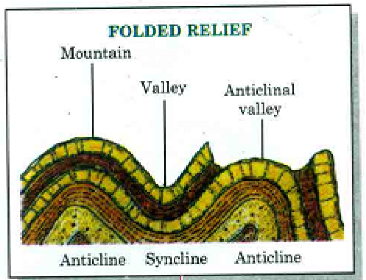
a) Gently bent without much deformation
b) Ascent of buoyant mantle material
c) Far from plate boundaries
d) Adirondack Mountains: Uplift of deep PreCambrian Igneous and Metamorphic rocks

The Adirondack Mountains of Northern New York

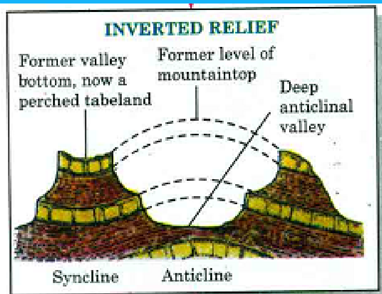


How Folded Mountains are Formed and then Altered Over the Course of Time

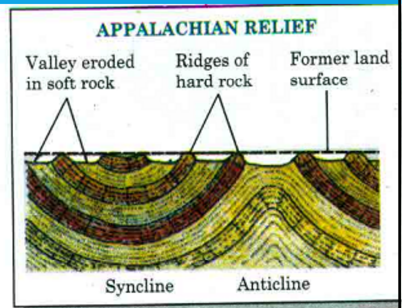
Rigid though rock is, great horizontal pressure can cause it to bend into wavelike folds. The folds usually occur in long parallel rows of mountain ridges separated by valleys, such as are found in the Zagros. The upward folds are termed **anticlines;** the intervening downwarped troughs are called **synclines.**



Erosion in time can mask the basic structure of the folds. The top of a fold may be worn away to form an anticlinal valley (*left*). Severe erosion can completely wear away the anticline, resulting in inverted relief (*center*). In this case the synclines-once the bottoms of valleys-are left standing high above their



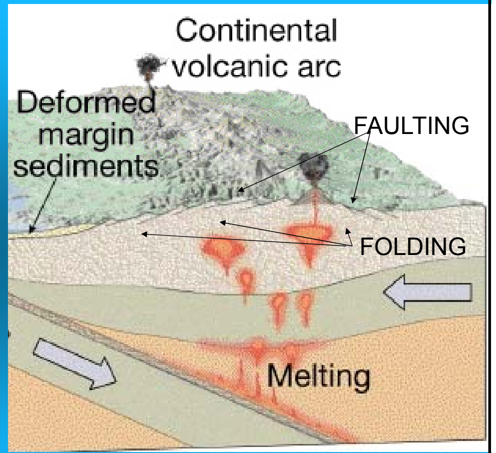
surroundings. In the case of so-called Appalachian relief (*right*), the folds are first eroded down to a flat surface. Renewed erosion then wears away the areas of soft rock to produce valleys separated by ridges of more resistant rock.



Truncated Dome

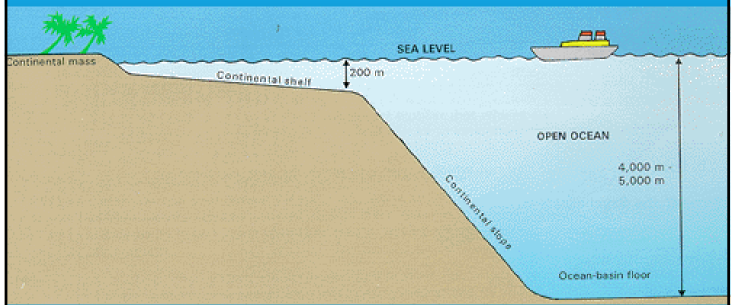
Fig. 11.19

Many folds in orogenic belts have in fact formed at depth and later been exposed at the surface by erosion of overlying rocks. On the other hand, rocks at or near the surface of the earth are under low confining pressure and low temperature, and tend to be BRITTLE and fracture when subjected to stress.



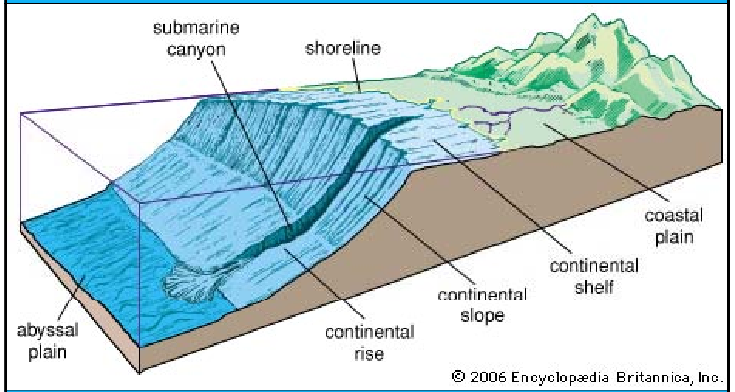
Geologic Features in the Ocean

Continental Shelf & Continental Slope



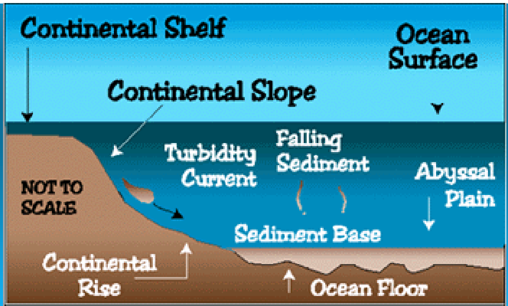
Continental Shelf

- The continental shelf is a submerged extension of the continental crust that slopes gently outward from the modern shoreline to the deep ocean basin.
- The continental shelf varies in width from being almost non-existent along some continental margins to extending outward for nearly 1500 kilometers (930 miles) in other places. On average it extends outward for about 80 kilometers (50 miles) and has an average slope of about 1 degree (2 meters/kilometer or 10 feet/mile).



Deep-Ocean Basin (covers 30% surface)

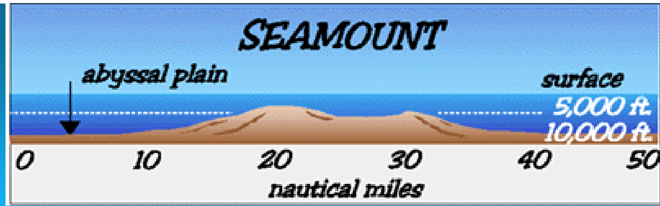
- **Abyssal plains** are nearly flat feature-less surfaces and may be the most level areas on Earth. They are very flat and consist of massive accumulations of sediment, deposited over the ocean floor. The average depth is 3.8 km.



Source: US Navy

Seamounts

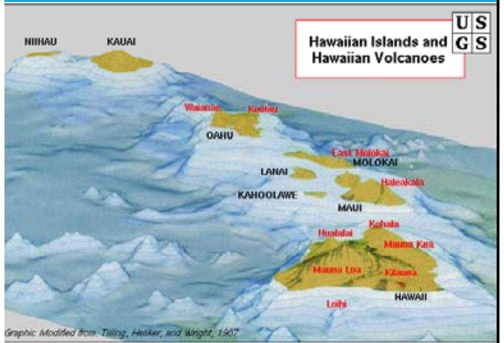
- Seamounts are steep-sided isolated submerged volcanic mountains (active or inactive) on the sea floor.
- Seamounts often occur far from mid-ocean ridges and trenches.



Source: US Navy

Seamounts rising above sea surface

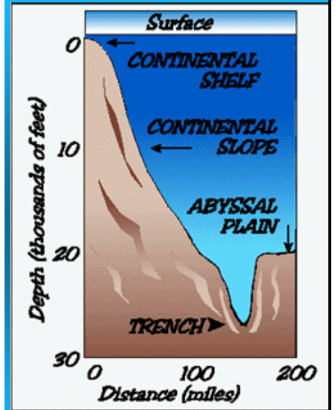
Seamounts often occur in long groups or "chains". Where seamounts poke above the sea surface, they form islands. Examples are Hawaiian Islands and Tahiti Islands.



Source: US Navy

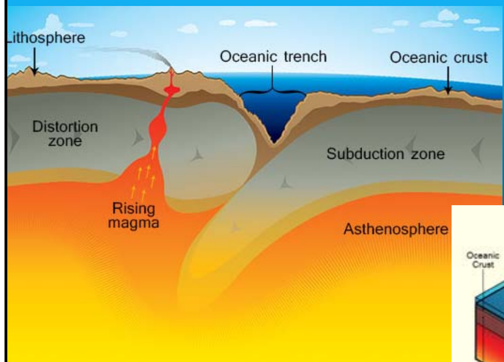
Trench

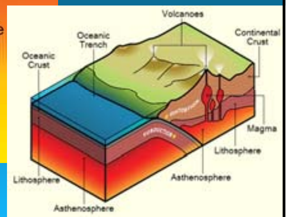
Ocean trenches may be defined as narrow V-shaped depressions formed over long distances were oceanic plate is subducting below another plate. **Trenches are associated with volcanic island arcs and areas of intense earthquake activity.** Marianas Trench in the South Pacific Ocean is the deepest (>10.6 km) trench.



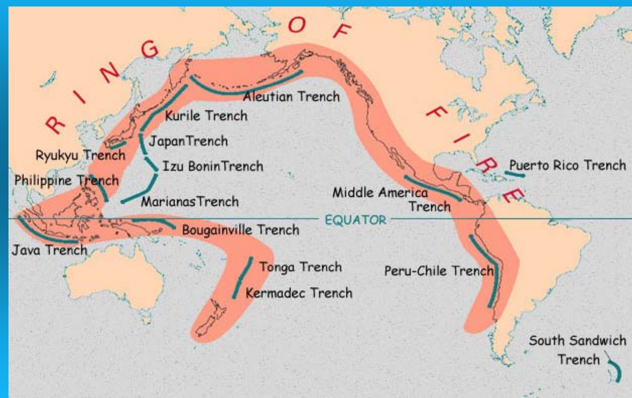
Source: US Navy

Formation of Oceanic Trench





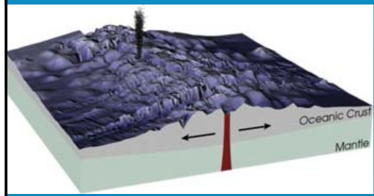
Most of Earth's deep-sea trenches are around the edges of the Pacific Ocean. This map shows the locations of these deep-sea trenches.

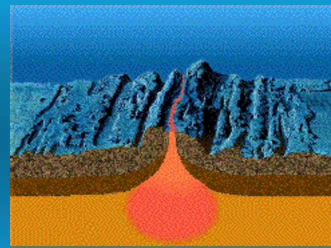


Mid-Ocean Ridges

- **Mid-ocean ridges are formed by rising magma along divergent plate boundaries.** New oceanic crust is formed along the narrow ridge crest, where magma rises and solidifies.
- **They form a single, connected, volcanic mountain range over thousands of km in length.** The Mid-Atlantic Ridge extends almost the entire length of the North and South Atlantic Ocean and is one of the most prominent subterranean ocean floor features. It rises 3000 meters above the ocean basin floor and is closely monitored by scientists.
- The Mid-Indian Ridge is another prominent feature, and it is actually a continuance of the Mid-Atlantic Ridge system, stretching from below South Africa up to India and Egypt.

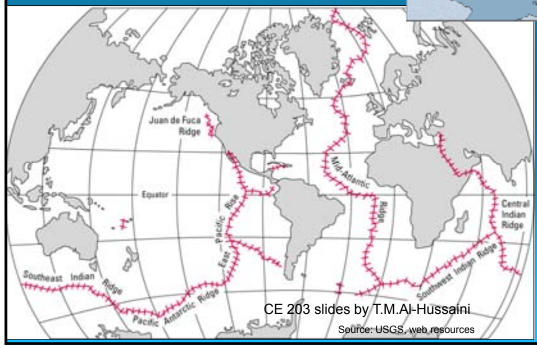
Formation of Mid-Ocean Ridges





Mid-Ocean Ridges

USGS created this "baseball" graphic to illustrate the locations of the major mid-ocean ridge systems. The continuous line marks the location and orientation of the ridge, and the cross-stitching represents potential fault patterns along the ridges. Because the ridges mark plate boundaries they are more or less continuous, but are differentiated by name relative to ocean basin or continental proximity.



Volcano

Volcanic Eruption

Due to the intense pressure inside the crust, the magma remains in a viscous state. But whenever, this pressure is released, because of the presence of fractures, fissures, and other weaker planes in the Earth's crust, the viscous hot matter melts, and injects along these weak surfaces. When the cracks extend up to the surface, the magmatic matter also starts erupting over toe ground, when it is called lava after its extrusion. This process of level intrusions (i.e., movement of magma within the Earth's crust) and eruptions is known as volcanism or volcanic activity.

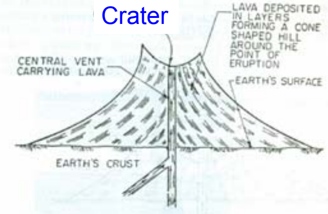
The lavas may erupt out on to the surface, either from long fissures extending over a considerable part of the Earth, or from centrally located chimney type vents. The former, normally quiet eruptions, are called fissure type eruptions (also called mass type eruptions) ; and the latter, generally violent explosive eruptions, are called central type eruptions.

Volcano

Violent naturally occurring central type eruptions where hot lava comes out **through a central vent** regularly or occasionally, are called volcanoes. A frequently erupting volcano is known as **active volcano** ; one with rare eruptions is called a **dormant volcano**; while the volcanoes which have stopped their eruptions since a long geological time, are called extinct or **dead volcano**.

Volcanoes, thus, throw out molten material on the ground surface, which get accumulated around the central opening or vent, forming a cone shaped mountain. Such mountains may largely vary in their height, ranging from a few hundred metres to thousands of metres. For example, the Cotopaxi (Ecuador), the highest active volcano of the world, has a height of 5974 m.; and the Aconcagua (Chile) an extinct volcano, is 6900 m in height.

A typical volcano is, thus, a conical or roughly conical hill or mountain, formed by the accumulation of lava and blasted rocks. With the continuing accumulation of such materials, this cone shaped hill grows in height and expands in lateral directions. The erupted products spread in such a way that a typical circular depression or pit, known as crater, is formed at the top of the hill. The size of the crater grows with the size of the volcano, and may range up to several km in diameter. At the end of lava eruption, the molten lava congeals, and pluggs the vent also.



In general, volcanoes have been found concentrated along mountain regions, where earth movements take place frequently (*i.e.* they occur in the regions of crustal unrest). They are also found in the marine areas near seas.

The **factors which are responsible for the origin of a volcano** include :

(*i*) *The presence of molten material below the Earth's crust* ;

(*ii*) *The presence of fissures or vents* (through which the molten material may erupt) which may occur along definite tracts or belts, and

(*iii*) *the factors which may cause the upward movement of magma,* such as orogenic movements.

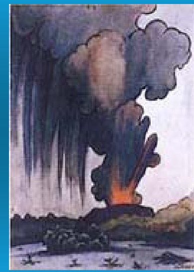
Considering all such factors, two causes have been attributed to the origin of volcanoes. They are explained below :

(1) It is assumed that the molten material exists locally beneath many regions of the Earth's crust. This molten mass is under high pressure and hence is in a viscous state. Whenever, curstal movements like those of mountain building activities (*i.e.* orogenic movements) take place in these local areas, the crust will develope fractures, thus releasing the pressure of the molten mass locally. The viscous hot matter will thus melt, and inject in these fractures, resulting in volcanism.

(2) It is possible that when water percolates through the Earth's crust, it may go deep and come in contact with molten rocks which are already at very high temperature (about 1000 to 1200°C). This will suddenly change the water into steam ; and this sudden change may result in creating an enormous pressure, sufficient to push up the molten matter up, through the points of least resistance (*i.e.* through the fractured zones). This possibility is supported by the facts that all volcanic eruptions are generally accompanied by huge quantities of steam, and also because many of the volcanoes of the world are situated near the seas.

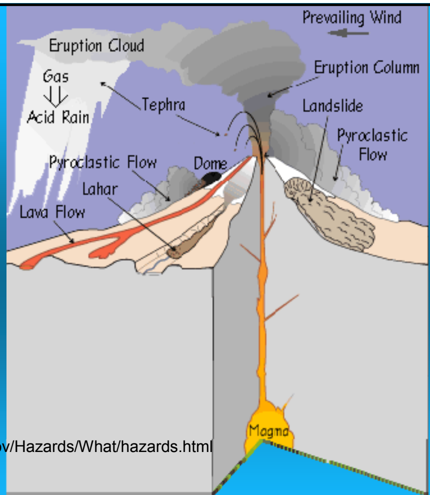
Volcanic hazards

- >1300 volcanoes known to have erupted in Holocene (last 10 000 years)
- ~500 classified as 'active' (i.e. known to have erupted in recorded history)
- Remainder classified as 'dormant' (may become active again) or 'extinct' (not expected to erupt again), but Vesuvius was thought to be extinct before AD 79!



Plus new vents: e.g. Paricutin (Michoacan, Mexico) shown erupting in 1943 (graphic by Diego Rivera)

Types of volcanic hazard

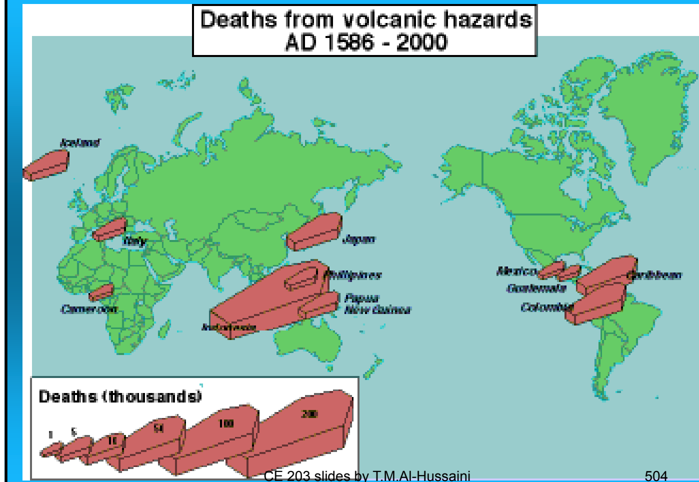


http://volcanoes.usgs.gov/Hazards/What/hazards.html

Volcano Distribution

Major volcanic eruptions since AD1600 (>8000 deaths)

Event	Date	Deaths	Hazard type
Laki, Iceland	1783	9000	Starvation
Unzen, Japan	1792	14300	70% by cone collapse; 30% by tsunami
Tambora, Indonesia	1815	92000	90% by starvation
Krakatoa, Indonesia	1883	36000	90% by starvation; <10% pyro. flows and tephra
Mt. Pel□e, Martinique	1902	29000	Pyroclastic flows
Nevada del Ruiz, Colombia	1985	25000	Lahars

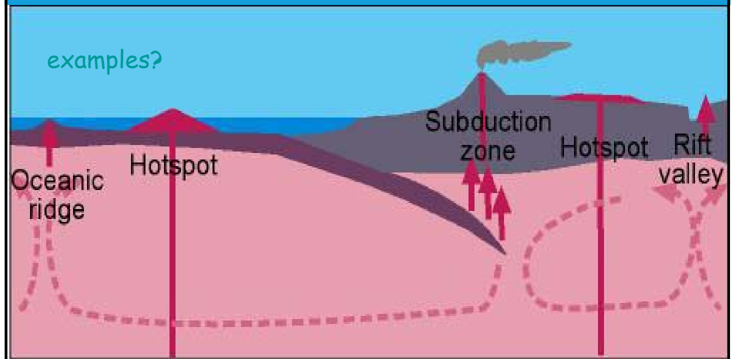


Volcanoes

Eruptive style and hazard depends on:

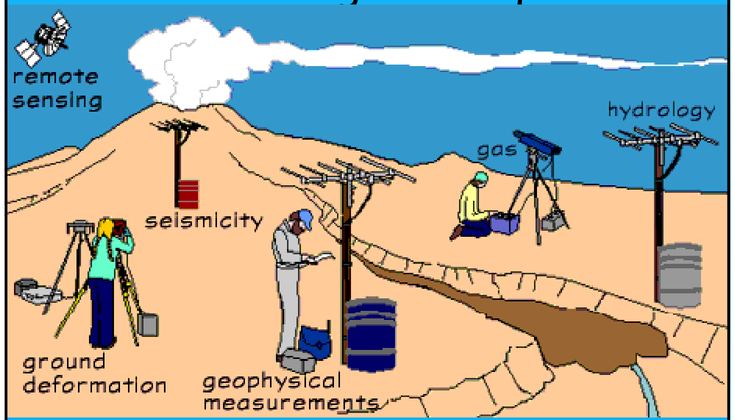
- Tectonic setting
- Depth of magma formation
- Rate of magma movement to the surface
- Percent and type of volatiles (gases)

Volcanoes - tectonic settings



	Oceanic ridge, Hotspots	Subduction zone
	Basic/Mafic volcanics	Acidic/Felsic volcanics
	•Low SiO2 •Fluid lava (10 m/s) •Low gas pressure (little explosive activity)	•High SiO2 •Viscous lava (3 m/s) •High gas pressure (explosive activity)

Monitoring techniques



Gaseous Products:

Steam (H_2O)– may lead to heavy rain - mudflows
Carbon dioxide (CO_2)
Sulphur dioxide (SO_2),
Hydrogen chloride (HCl) and Hydrogen fluoride (HF)
Hydrogen sulphide (H_2S)

Liquid Products:

Lava – excessively hot liquid (900-1200°C)
- Basaltic lavas – Less viscous, more mobile (0.3-10 km/hr), travel up to 150 km. Low silica, Mafic
- Acidic/Felsic lavas – silica rich, highly viscous.

These lavas on cooling produces extrusive igneous rocks

Solid Products:

Cinder – Rock fragments (few mm to few cm size)
Volcanic dust/Volcanic ash – dust or ash like fine particles
Volcanic tuff – Rock composed of volcanic dust or ash
Breccia – Rock formed from consolidation of various size fragments.
Volcanic bombs – large size particles greater than 64 mm – various shapes

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Volcanic Landforms

- An erupting volcano will produce a number of distinct landforms including:
  - A. Volcanic cones
  - B. Flood basalts
  - C. Calderas

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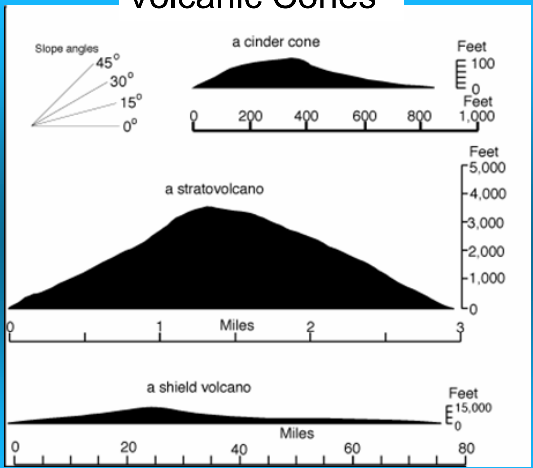
Volcanic Cones



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Stratovolcano

Stratocones or Composite cones are imposing volcanic mountains, with sloping peaks rising several thousand meters above the landscape. Stratocones are made up of layers of lava, volcanic ash, and fragmented rocks. These layers are built up over time as the volcano erupts through a vent or group of vents at the summit’s crater. One of the most famous stratocones in the world is Mount Fuji, Japan, 3776 m above the surrounding landscape. Mount Fuji last erupted in 1707, but is still considered an active volcano.

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Cinder cone

In a cinder cone, lava erupts from a small vent in the crust and 'sprays' melted rock fragments into the air where they then fall back to earth in a pile. These rock fragments are glassy, gas-filled chunks of lava called cinders that cool rapidly as they sail through the air and land next to the vent opening, slowly accumulating in the geometric shape of a cone. Cinder cones tend to be small, hill-sized volcanoes that range in height from tens to hundreds of meters high. Cinder cones are characterized by their steep sides and conical shape.

Cinder cones may appear as single volcanoes or as secondary volcanoes on larger existing stratovolcanoes or shieldvolcanoes. Mauna Kea, a volcano on the American island of Hawaii, and Mount Etna, a volcano on the Italian island of Sicily, are both covered with hundreds of cinder cones.

Cinder cone in Utah, USA

Shield Volcano

Slow and gradual accumulation of thin layers of lava build up over long periods of time, forming a long, shield-shaped volcano. Gentle sloping sides.

B) Flood basalts

- A flood basalt is the result of a giant volcanic eruption or series of eruptions that coats large stretches of land or the ocean floor with basalt lava. Eleven distinct flood basalt episodes occurred in the past 250 million years, resulting in large volcanic provinces, creating plateaus and mountain ranges on earth.
- They are formed by flow of very low viscosity magma, which is why they 'flood' rather than form taller volcanoes.
- The Deccan Traps of central India, the Siberian Traps, and the Columbia River Plateau of western North America are three regions covered by prehistoric flood basalts.

Deccan Traps located in west-central India are one of the largest volcanic features on Earth. They consist of multiple layers of solidified flood basalt that together are more than 2 km thick, today covering an area of 500,000 km^2. Deccan Traps began forming 66 million years ago, at the end of the Cretaceous period and eruptions took place less than 30,000 years.

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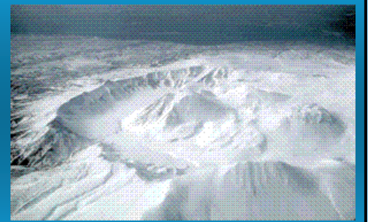
C) Calderas

– Large depressions (> 1km) from violent eruptions
– Ugashik Caldera, AK



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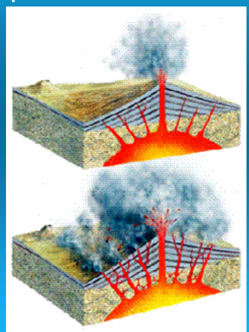
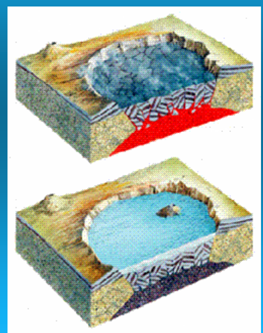
Formation of Calderas

Volcano rapidly empties its magma chamber, and support is lost



Overlying material collapses into magma chamber and Caldera forms



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Lake within a Volcano within Lake within a Volcano, Phillipines 2014

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Various Types of Lakes and their formation

A lake may be defined as water-filled depression of a fairly large size, existing on the Earth's surface. The size of a lake is somewhere between a pond and a sea. The water of the lake is generally semi-stagnant, as it has got a definite source of supply, and generally an outlet.

Depending upon the manner in which a *basin (depression)* gets filled up with water to form a lake, there can be nine types of lakes:

(1) Tectonic Lakes or Crustal Lakes. The depressions formed in the Earth's crust by tectonic movements *(displacements)* like folding, faulting etc, may result in the formation of basins for such lakes. This type of lakes are generally quite permanent.

(2) Barrier Lakes: These lakes are formed along river valleys by natural obstructions created across their courses. The lakes so formed on the upstream side of the obstruction may be called as a *barrier lake. The obstruction may be caused by rock slides, or by alluvial or glacial barriers. The alluvial barriers might be deposited* by excessive deposition caused by extinct glaciers or river flows, during the past history. There are many such lakes located in the higher ranges of Himalayas in India and Tibet.

(3) Rock-Basins: These may be defined as the hollows or depressions scooped out by glaciers on the rocky floors of the river valleys during the past geological times. These depressions or lake basins may get their water supply from the melting of glaciers of the upper regions or from rivers and rains. There are many fresh water lakes located in the higher ranges of Himalayas, and particularly in the Tibetan Himalayas, which are believed to be of such an origin.

(4) Volcanic Lakes or Crater Lakes. The crater or caldera of an extinct volcano may get filled up with water, and thus acting as a lake basin, called volcanic lake or crater lake. The Gohana lake of Garhwal (India) is believed to have been formed in this manner.

(5) Meteoric Lakes. Sometimes, the meteorites hit the earth surface with great impact, and as a result, may produce large hollows or depressions on the crust. The lakes formed in such basins may be called as meteoric lakes. Such lakes are generally very rare.

(6) Desert Lakes. In arid regions (deserts), sometimes, the winds may erode down the land surface to such an extent that the water table is exposed to form an *oasis (as discussed earlier). The lake so* formed at the site of the depression may be called as an oasis lake. The Quattara depression of Western Egypt provides an excellent example of such a type of lake basin. It is 300 km long, 140 km wide, and 125 m deep. The Sambar and other salt lakes of Rajasthan (India), which provide common salt on a large scale, are of *aeolian origin ;* formed by the rain water getting deposited in the depressions amongst the sand dunes.

(7) Deltaic Lakes. Sometimes, the inland *off-shoots of a sea may* get separated from the main body of the sea by deposition of spits, bars, etc.; forming a *deltaic lake on the land margin. The Chilka* lake in Orissa is only a few feet deep.

(8) Ox-bow Lakes. *Ox-bow lakes* are bodies of water standing in the deserted loops of a meandering river. Certain geologists believe that some of the lakes of Kashmere-Himalayas are ox-bow lakes instead of rock basins.

(9) Artifical Lakes. The lake formed on the upstream side of an artificial dam constructed across a river may be called as an *artificial lake.* Example is Kaptai Lake.

Geoogical work of Lakes

The lakes, because of their smaller size (compared to sea or ocean) are not the active agents of geological work. But, large sized lakes can perform the geological work of erosion and deposition just like a sea, although the work will be of much less magnitude. Only in such big sized lakes, the waves, capable of performing erosive work on shore rocks, are generated. Their most important work is, however, deposition. Most of the lake basins are bodies of standing water, like reservoirs; and they go on receiving sediments from time to time from the feeding rivers, glaciers, or the winds passing over them. They may also absorb some of the sediments eroded from their shores by waves.
The sediments brought into a lake, are generally very well sorted and screened, particularly in deep lakes. The rate of flow and the amount of sediment brought into a lake are also responsible for the quality of screening. Shallow lakes and lakes filled up rapidly by large quantities of rock-waste, may show poor sorting. In any case, the lake basins get gradually filled up with sediments; and thus, get vanished over a passage of time, leaving behind ponds, swamps and marshes.

Karst Landform

Karst Landforms

Karst is a term used to describe landscapes that are formed by chemical weathering process controlled by groundwater activity. Karst landscapes are predominantly composed of limestone rock that contains ≥ 70 percent calcium carbonate.

- Caverns (Caves)
- Sinkholes
- Disappearing Streams
- Springs
- Towers

Onondaga Cave in Missouri is a karst landform formed by chemical solution in carbonate limestone rocks. Features within Onondaga Cave include stalagmites, stalactites, dripstones and active flowstone deposits.

Sinkholes

- Sinkholes are collapsed limestone features that develop in karst landscapes. Sinkholes form when the limestone bedrock is chemically weathered by naturally occurring chemicals in the ground water. The ground water slowly dissolves the limestone rock below the surface until it eventually becomes unstable and collapses creating local depressional features.
- Sinkholes pose a threat to developed areas, because if they occur beneath houses or other infrastructure they may collapse with the sinkhole.
- Increased pressure on water resources and depleted ground water tables can trigger sinkholes to collapse under the pressure of gravity or the void formed by the depleted ground water.

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