Minerals of the world

volume2

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2010

First published 2010

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INTRODUCTION

The Origin of the Earth

Origin of the solar system.

How and when did it begin? Any theory must answer the following:

1. All planets revolve around the Sun in the same direction in elliptical orbits that lie in the same plane. Pluto is a slight exception, probably a captured comet.
2. All planets except Uranus (which rolls) and perhaps Venus and Mercury which are in tidal lock with the Sun, rotate in the same direction (counterclockwise).
3. The planets lie at regular geometric distances from the Sun. Each about 2X the distance of the previous.
4. 99.9% of the angular momentum is in the planets.
5. Separated into two distinct groups:

    - Terrestrial (inner) planets of high density. Elements present are iron, oxygen, silicon, and magnesium. All are of roughly the same size.
    - Jovian (outer) planets of low density. Dominated by hydogen, helium, ammonia and methane. All are quite large. Density of Saturn less than that of water.

Hypotheses to explain the origin of the solar system

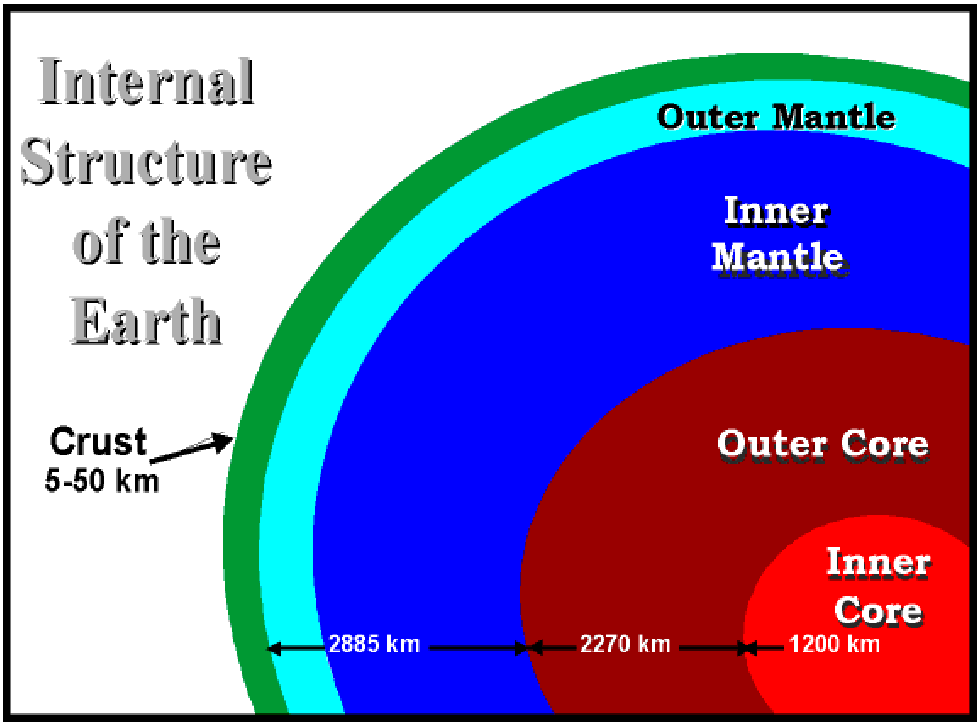
1. **Nebular Hypothesis** - Proposed by Kant in 1755. Solar system began as a large rotating dust cloud. Explains 1 and 2 above. Cloud cools and contracts. Can use the analogy of a figure skater to explain how cloud spins faster as it contracts. Eventually spins off rings that agglomerate into planets. Big problem is the presence of all the angular momentum in the planets. Sun should be spinning faster.
2. **Collision Hypothesis** - Begins in same manner as above with gas cloud cooling and contracting. Passing star yanks tongues of material from the proto-sun. Problem is that an expanding gas cloud should overcome the gravitational attraction of the Sun.
3. **Recent Theory** - Revives nebular hypothesis. Sun condenses under the force of rotation and gravity. Compression causes temperature to exceed one million −C. Thermonuclear reaction occurs which synthesizes the various elements. Material is blown out into space. As tempereature falls condensation begins with higher temperature substances (heavier elements) first to condense. Hence, heavy planets are near Sun and lighter ones farther out.

Gross Structure of the Earth's Interior (Figure below)

1) Crust - 5-50 km thick. Density 2.85 gr/cm^3

2) Mantle - 2900 km thick. Density 3.3 gr/cm^3

3) Core - 3400 km thick. Density 15 gr/cm^3



Knowledge of the interior structure of the Earth is based largely on the study of seismic waves as they travel through the Earth and studies of meteorites, which are thought to represent fragments of extraterrestrial planetary material.

Planetary Evolution

No recent hypothesis. Thought that planetesimals form by accretion of condensed clumps of silicon. oxygen, iron and magnesium. Accreted material attracted to other accreted material by the force of gravity. Compression provides heat. Further infalling chunks of material convert energy of motion to heat energy. Finally radioactivity generates additional heat. All three combine to heat Earth to the melting point. Iron and magnesium sink to the core (iron catastrophe). This differentiates the Earth into a core and mantle/crust.

Elemental Composition of the Earth		
Element	**Crust (wt.%)**	**Core (wt.%)**
Oxygen	46.6	30
Silicon	27.7	15
Aluminum	8.1	1
Iron	5.0	35
Calcium	3.6	--
Sodium	2.8	--
Potassium	2.6	--
Magnesium	2.1	17

Looking at the Crust

1. Bedrock - Solid outcropping bodies of rock. Example is the San Gabriel Mountains. Three distinct types of bedrock:

   a) Igneous rock - Formed from the cooling of a magma.

   b) Sedimentary rock - Rocks formed from fragments of pre-existing rocks at the Earth's surface in response to weathering.

   c) Metamorphic rock - Rocks which are changed from their original nature in response to heat and pressure.

Geologic Time

Basic Concepts

1. **Principle of Uniformity** - Proposed by James Hutton (aka Father of Geology). "The Present is the Key to the Past". Processes that operate on the Earth today probably operated in a similar manner in the past. Does not imply they operated at the same rate.
2. **Law of Superposition -** Proposed by Nicholas Steno in 1669. In any sequence of layered rocks that have not been disturbed, the oldest layer is on the bottom and the youngest on the top.

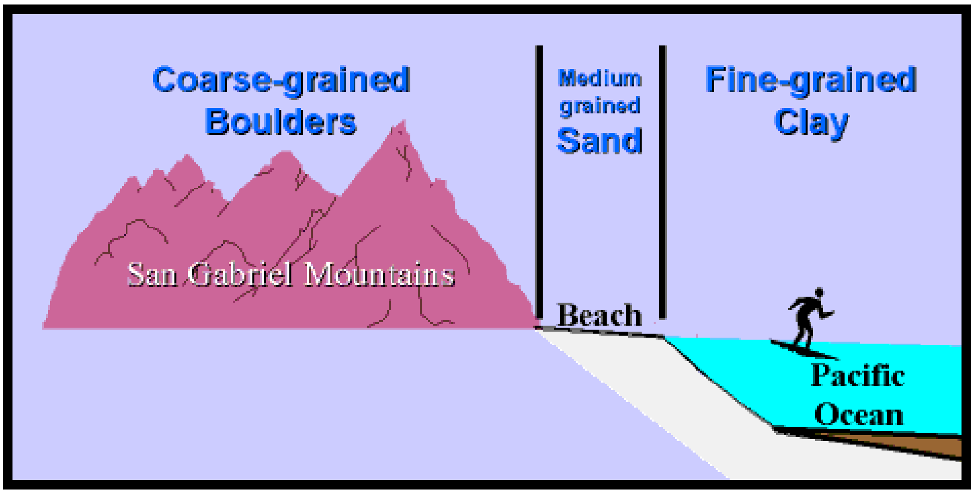
3. **Law of Original Horizontality** - (Steno) Sediments are deposited in layers parallel to the Earth's surface.
4. **Law of Cross Cutting Relationships** - When one rock unit cross cuts another, the one that does the cross cutting is the younger.
5. **Law of Faunal Succession** - W. Smith - Rocks with similar fossils are the same age.

Types of Geologic Time

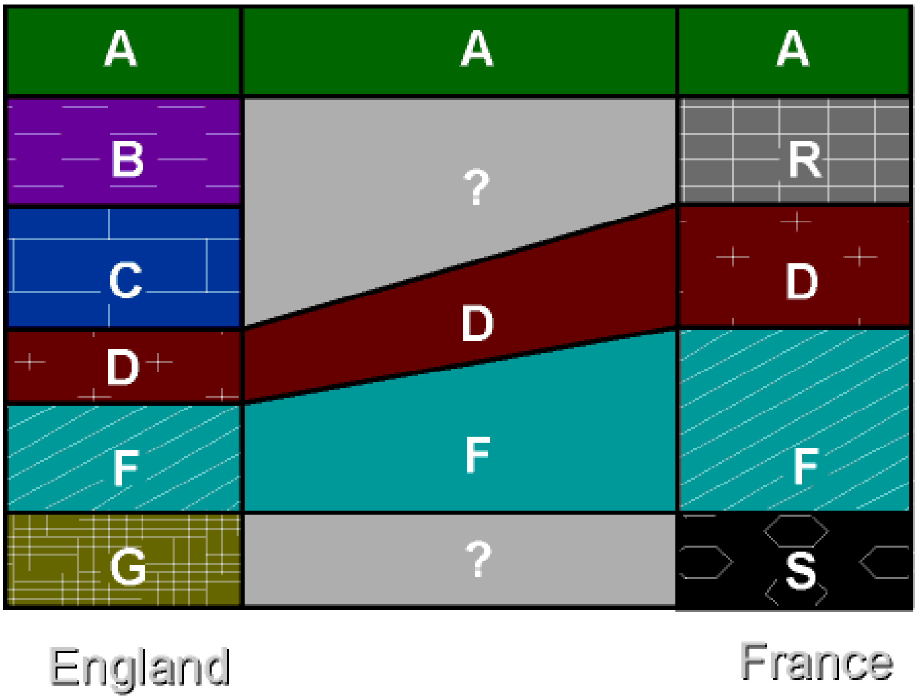
A. **Absolute Time** - The actual age of a rock or geologic event in years. Based on radioactive age dates.
B. **Relative Time** - The relative of age of one rock compared to another. Is this rock younger or older than that rock?

Relative Time

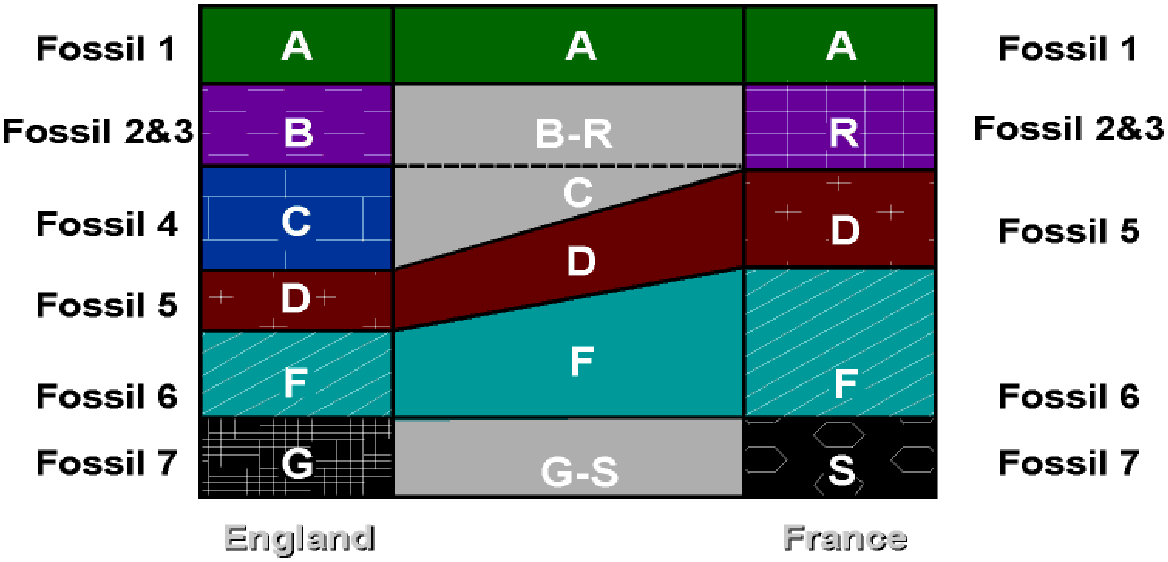
First attempts to establish ages based on relative age dating and the basic principles given above. Go through figures on relative age dating.



These attempts worked only over short distances (physical correlation). The problem is what happens over longer distances. Introduce the concept of differing sedimentary facies due to differences in the environments of deposition. Use analogy of So. Cal. (**Figure**) showing different environments of deposition. Another example is England and France (**Figure**).



Second figure shows how the correlation using fossils in England and France was much more successful (**Figure**). With fossil assemblages it is possible to create a chronologic sequence of rocks based on relative ages. This sequence is termed the **Geologic Column**.



Geologic Time Scale

1. **Precambrian -** Thought to represent all rocks deposited prior to the evolution of life. Now recognized to be period of time prior to the evolution of complex organisms. (4/5 ths of earth's history)
2. **Paleozoic** - Generally period of time when life was confined to the seas. (about 1/2 of the remaining 1/5th)
3. **Mesozoic** - Age of reptiles and other primitive land animals. Advanced land plants (most of the remaining span of time)
4. **Cenozoic** - Age of mammals. (about 1% of the earth's history)

Absolute Time

While relative time provides useful information regarding the timing of one event relative to another, it does nothing to answer the fundamental question about the age of the Earth.

Early Attempts at Absolute Age Dating

1. Bible - Archbishop Ussher - 9 AM, Oct. 26, 4004 B.C.
2. Rate of Cooling of the Earth - Lord Kelvin estimates the Earth is 70 MY old. Unfortunately, he was unaware of radioactive decay and neglected its contribution to the total heat being lost by the Earth.
3. Salt in the Oceans - Estimates of about 90 MY based on this method. It neglects all the salt in trapped in sedimentary rocks.
4. Rate of Sediment Accumulation - 3 MY to 1584 MY. Very inaccurate due to problems determining the total thickness of all sediments accumulated through geologic time.

Radioactive Decay

Matter - Anything that occupies space and can be seen by the human eye. Definition serves well until the first microscope is built (17th century). Scientists realize there are particles smaller than the eye can see.

Atom - The smallest particle of which matter is composed.

Scientists could not see atoms, but over centuries they devised a model of the atom based on simple logic. They reasoned the atom had to be composed of at least two sub-atomic particles, which they termed the proton (+) and the electron (-). The latter revolved in orbitals around the former, analogous to the revolution of the planets around the Sun. Mass deficiencies lead them to propose a third sub-atomic particle, the neutron (no charge) which they place in the nucleus with the protons. From this was born the concept of the element.

Element - A unique combination of protons, electrons and neutrons. Each element differs in the number of protons in the nucleus.

Atomic Number - The number of protons in an atom of a particular element.

Atomic Weight - The number of protons and neutrons. Electrons have less than 1% of the total mass of an atom and can be ignored.

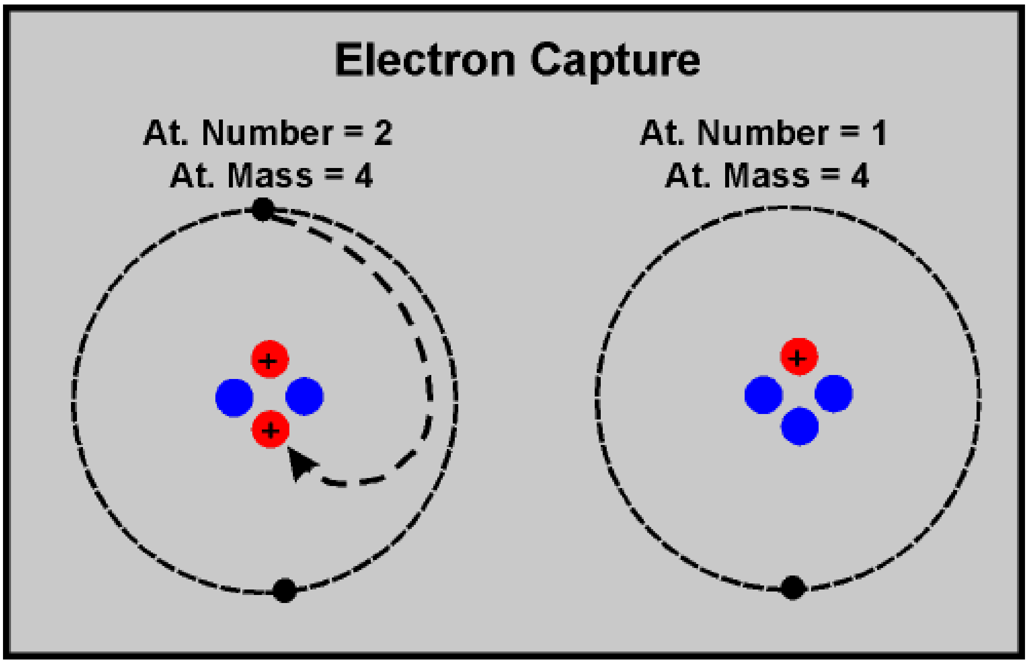
Late in the 19th century the theory of radioactivity was first proposed. It explained why certain elements were unstable, that is, they were observed to spontaneously decay to other differing elements. Central to this theory was the concept of the isotope.

Isotope - An atom of an element that differs from another atom of the same element only by the number of neutrons in the nucleus. Example ^{12}C ^{13}C ^{14}C

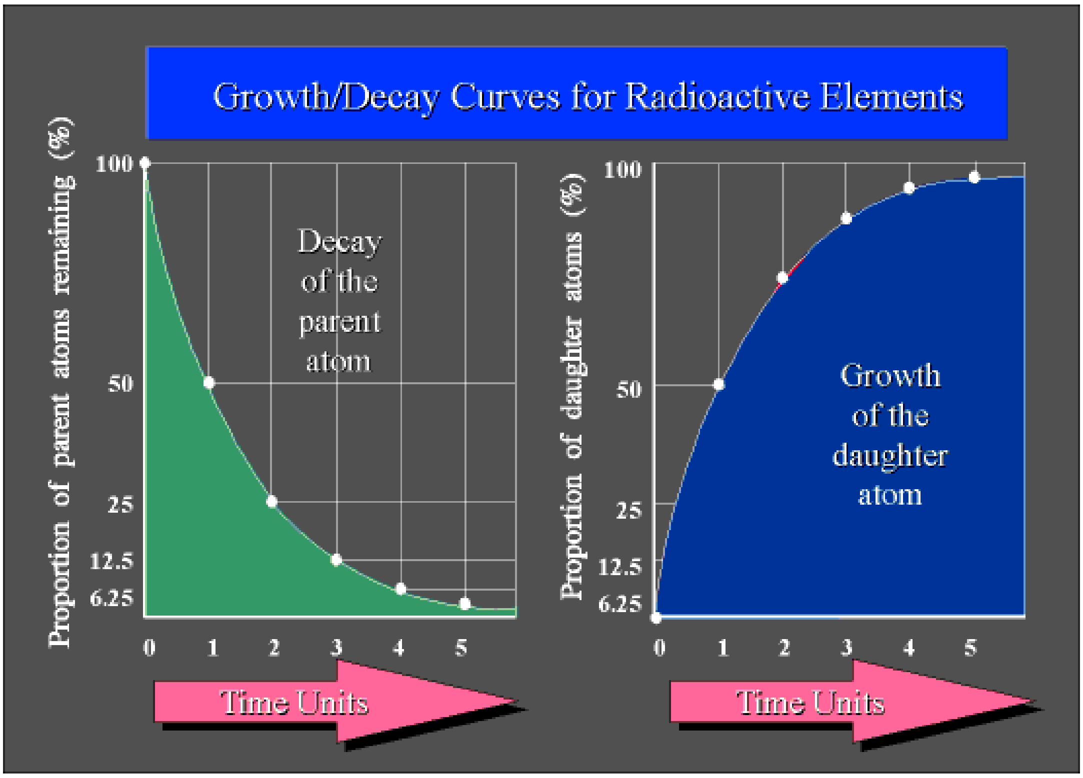
Certain isotopes are radiogenic (unstable) and with time will decay to another element. There are several decay schemes.

Decay Schemes

a. alpha decay - emission of a helium nuclei (2 protons and 2 neutrons). The result is a loss of 2 in atomic number and 4 atomic weight. The decay of uranium to lead follows this scheme.
b. beta decay - a neutron decays to a proton with the emission of a beta particle (electron). The result is a gain in 1 in atomic number and no change in mass. An example is the decay of rubidium to strontium.
c. electron capture - an electron falls into the nucleus and combines with a proton to form a neutron. The result is a loss of 1 in atomic number and no change in mass. An example is the decay of potassium to argon. (**Figure**)



The usefulness of radioactive decay to geology comes from the fact that the rate of decay is a constant that is unaffected by any physical process. **Figure** shows how the decay of parent atoms and growth of daughter atoms with time.



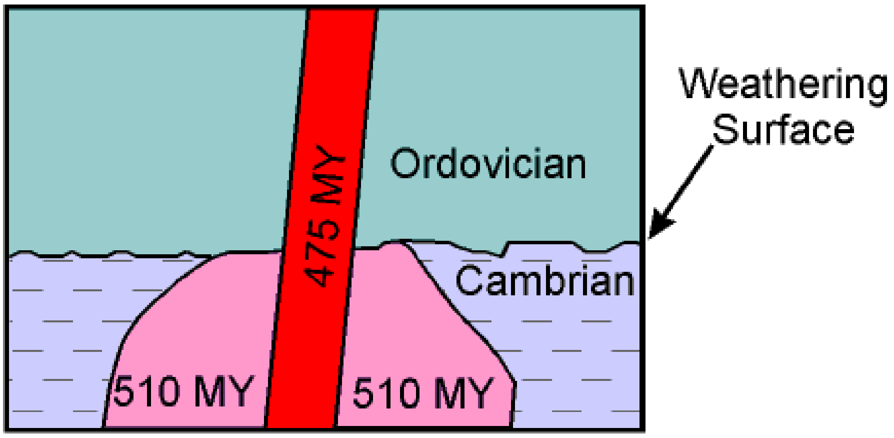
How does it work in nature?

1. Magma is generated and begins to cool. Radioactive decay occurs throughout this process, but since the magma is a liquid the parent atoms quickly separate from the daughter atoms.
2. When the rock solidifies that separation can no longer occur and the newly formed daughter atoms are trapped.
3. Scientists sample the rock and in the lab release both the parent and daughter atoms, counting each.
4. The decay rates have been experimentally determined and from the decay equation the age of the rock can measured.

Using this method we can date:

- most igneous rocks
- very few sedimentary rocks
- organic material

Since we cannot age date most sedimentary rocks and the geologic column was complied on the basis of sedimentary rocks we have a slight problem assigning ages to rocks in the geologic column. **Figure** shows how we reconciled this problem.



Beginning of Ordovician
between 475 MY and 510 MY

The age of the Earth based on

1. meteorites - 4.5 BY
2. moon rocks - 4.5 BY
3. minerals - 4.0 BY

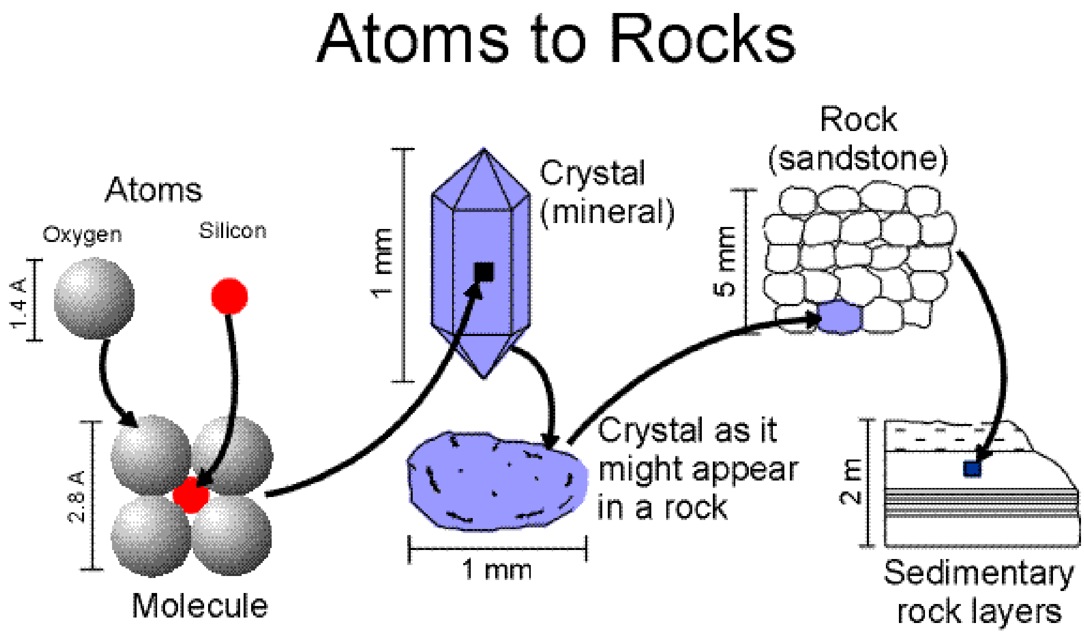
From these the age of the Earth is at least 4.5 BY and generally agreed to be **4.6 BY**.

MINERALS

Minerals - Defined

1. Naturally occurring
2. Inorganic
3. Fixed chemical formula
4. Unique orderly internal arrangement of atoms (crystalline)

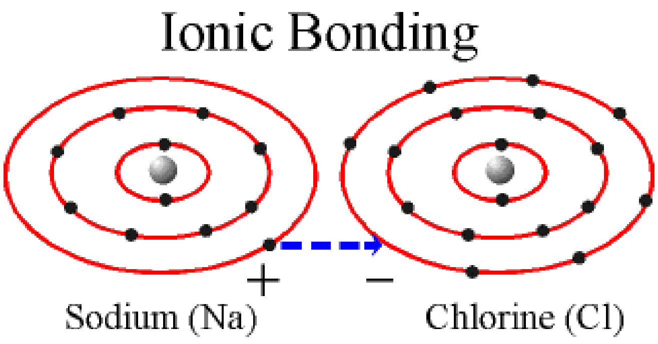
Atoms to Rocks (**Figure**) - Shows how the mineral is the basic building block of the geologist. In order to build minerals the atoms must join together. The process of the joining of atoms is called bonding.



There are several mechanisms through which bonding can occur but from the geologic standpoint only two are important:

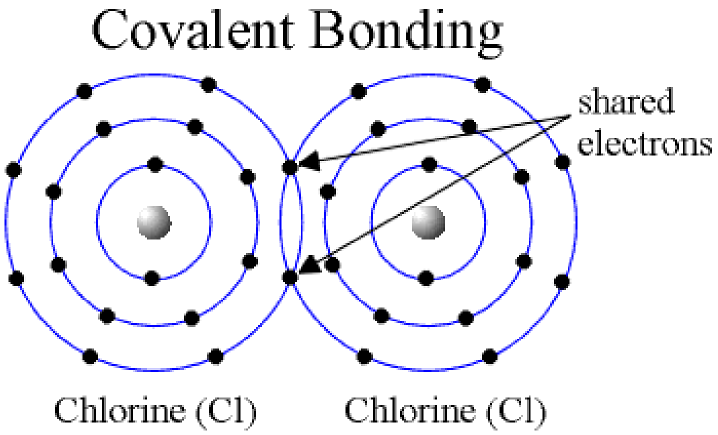
- Ionic
- Covalent

Figure for NaCl. All atoms attempt to achieve the stable configuration of eight electrons in the outer most shell. To do this they can gain or lose electrons. This gain or loss causes the atoms to become charged since there is now an imbalance between positive charges (protons) and negative charges (electrons). For NaCl; chlorine gains an electron and hence a negative charge while sodium does the opposite. Ionic bonds are generally weak and many of the compounds resulting from these bonds are soluble in water.



Covalent bonds result from the sharing of electrons. See the Cl-Cl Figure. Each chlorine shares one of its outer most electrons with an adjacent chlorine atom. This sharing results in stronger bonds, particularly where multiple electrons are shared.

Crystals are built by this sharing or overlapping of electron orbitals. Since only certain arrangements minimize the mutual repulsive forces between electrons these are favored giving each crystal/mineral its unique internal geometric arrangement.



Physical Properties

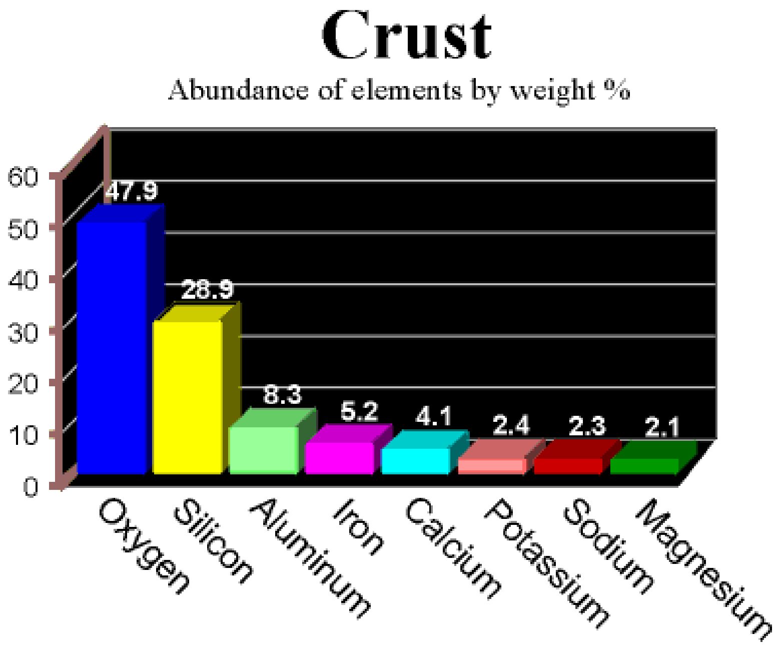
Properties of minerals that the eye can readily discern. All physical properties are to a large extent a function of the orderly nature of atoms making up the crystals and how those atoms are joined to build the crystal structure. Let痴 look at *some* physical properties:

- Color - Probably the least reliable of the physical properties. Caused by impurities or lattice defects in the crystals. Example the yellow of sulfur or green of malachite.
- Streak - The color of a powdered sample of a mineral. More reliable than color since same mineral seems to have same streak regardless of color of hand sample. Drawback is that many minerals have a white or colorless streak. Example the red-brown streak of hematite.
- Hardness - The ability of one mineral to scratch another or an object of known hardness. Hardness is directly related to the strength of the bonds.
- Cleavage - (Figure) The tendency of a mineral to split along certain preferred planes. A function of a weaker bonds in one or more planes or directions. Can have as many as 6 directions or as few as one. If a mineral does not have cleavage it is said to have fracture. Example: the concoidal fracture of quartz.

- Specific Gravity - The weight of a mineral compared to the weight of an equal volume of water. Can use heft as a crude estimate of specific gravity. Most silicates 2-3. Metallic minerals 4-10. A function of atomic packing.
- Luster - Appearance of a mineral when held up to the light. Terms most commonly used are metallic and nonmetallic. Metallic luster a function of metallic bonding. Other terms waxy, resinous, vitreous, earthy. A function of the interaction of light with the outer most shell of electrons.

Classification of Minerals

A classification of minerals is a necessity if we are to talk about them since there are over three thousand different minerals. We use the *anion classification* system in introductory classes to pigeonhole similar minerals. This is because minerals with common anions share many common physical properties. Before discussing the classification let痴 examine the abundance of elements in the earth's crust (Figure). We can expect that the most common minerals will be dominated by the most abundant elements (see below). Silicates (built from silicon and oxygen) are by far and away the most important/common minerals. Common Rock Forming Minerals table lists only the 10 most common minerals but they comprise 98% (by volume) of all minerals at the Earth痴 surface.



The Common Rock Forming Minerals

- Feldspar (silicate)
- Quartz (silicate)
- Muscovite (silicate)

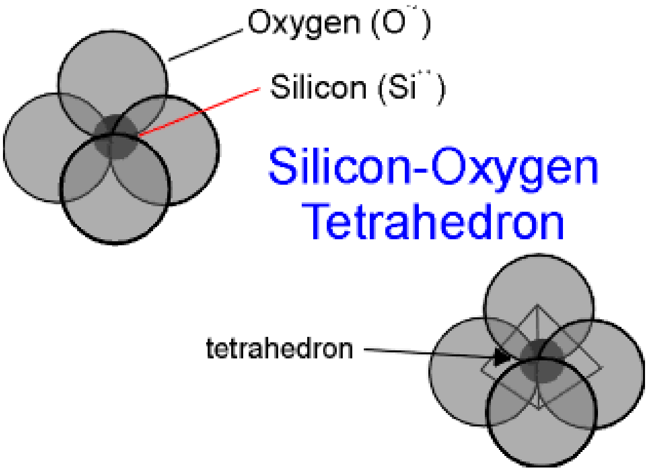
Ferromagnesians

- Olivine (silicate)
- Pyroxene (silicate)
- Amphibole (silicate)
- Biotite (silicate)
- Muscovite (silicate)

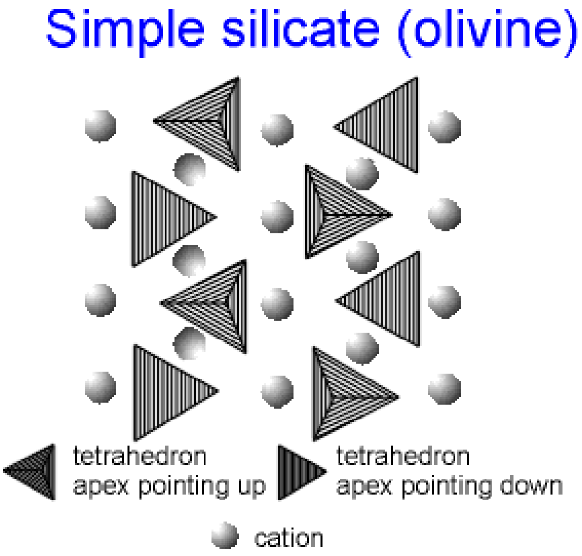
- Calcite (not a silicate)

Silicates

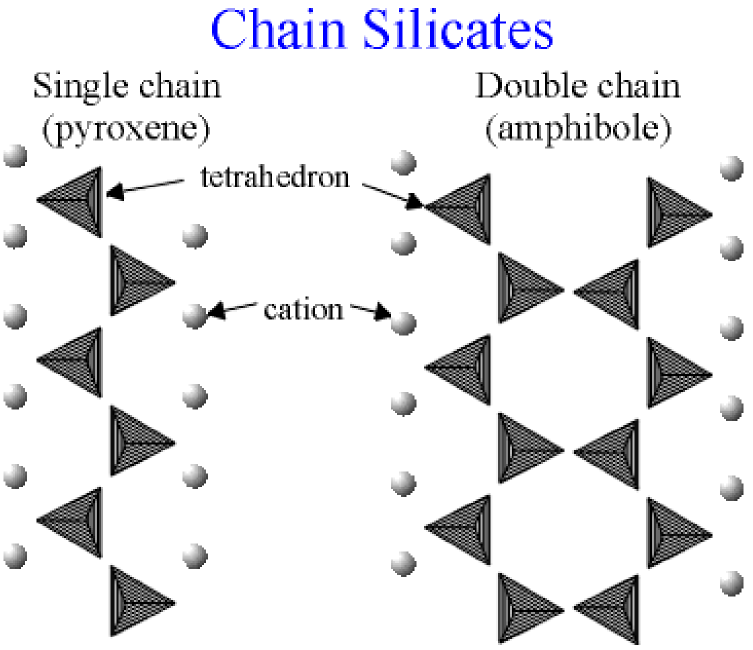
Consists of a small silicon atom with a +4 charge surrounded in tetrahedral fashion by four larger oxygen atoms each having a -2 charge (Figure). Net charge on the anion group is -4. To satisfy this charge deficiency the SiO_4 tetrahedra can either bond with cations (Fe, Mg, Ca, K, Na) or join with other SiO_4 tetrahedra through oxygen sharing.



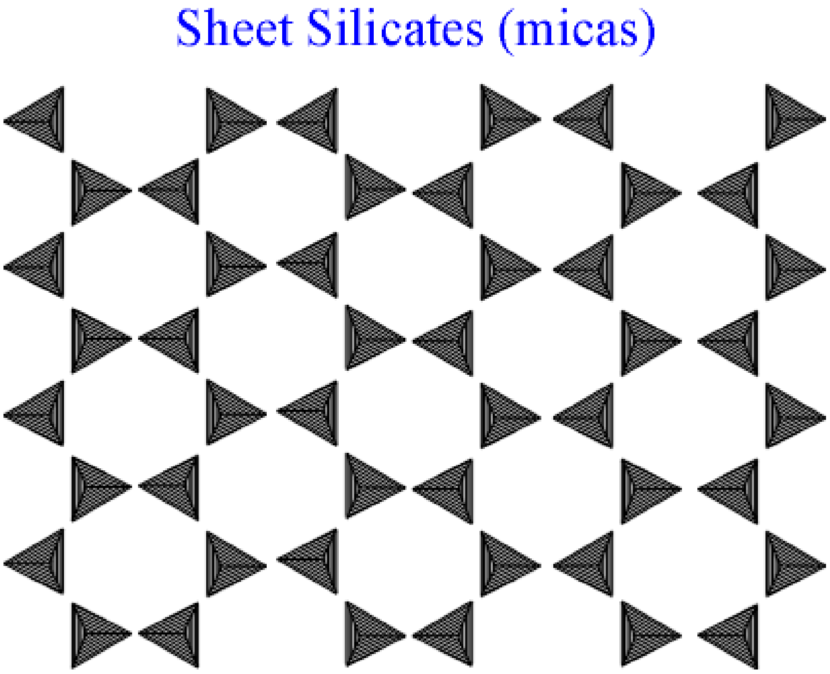
A) Simple silicates (Figure) Simplest structure in which each tetrahedra bonds to cations, usually Ca, Fe or Mg. Olivine is an example. Also the most dense of the silicates due to the close packing of the tetrahedra. Due to cation-tetrahedra bonds there are no stronger or weaker bonds and hence no cleavage.



B) Chain silicates (Figure) Can be either single or double chain silicates. Single chains share two basal oxygen while the double chain shares three. Two examples of this group are the pyroxenes (single chain) and amphiboles (double chain). Since the Si-O bonds are stronger than the tetrahedra-cation bonds this subgroup has fairly good cleavage in two directions.



C) Sheet silicates (Figure) Involves sharing of all basal oxygens to form a sheet of silicate tetrahedra. On top of this layer is a layer of cations, then another sheet of silicates, etc. etc. This gives the well developed basal cleavage in this group. Common sheet silicates are the micas.



D) Framework silicates - All four oxygens are shared to build up a framework of tetrahedra. Good example is quartz.

Other Anion Groups (See Slides in Class)

Carbonates - Consist of cation plus the carbonate anion (CO_3^{-2}). Important minerals calcite (calcium carbonate) and dolomite (calcium, magnesium carbonate). Calcite (limestone) the most important constituent in cement.

Oxides - Consist of oxygen plus a cation, often Fe, Ti, Al, Cu, or Cr. Important oxides include hematite (Fe oxide) magnetite (Fe oxide). Major source of world痴 iron, aluminum and chromium.

Sulfides - Sulfur plus a metallic cation. Most of our important ore minerals are in this group. Includes galena (PbS), pyrite (FeS_2) and numerous copper sulfides. Another important group of ore minerals.

Other Groups

a) Sulfates ($S0_4$) - Gypsum used for drywall

b) Halides (Cl,F,Br) - Rock salt

c) Phosphates ($P0_4$) - Apatite for fertilizer

IGNEOUS ROCKS

Rocks - Aggregates of minerals

Igneous Rocks - Rocks formed by crystallization from a melt (magma)

1. Extrusive (**volcanic**) - produced when magma flows on the earth's surface
2. Intrusive (**plutonic**) - produced when magma solidifies at depth beneath the earth.

Classification of Igneous Rocks

Process-oriented. Based on the rate of cooling of the igneous rocks and their resultant grain size.

Texture - size, shape and arrangement of mineral grains in a rock.

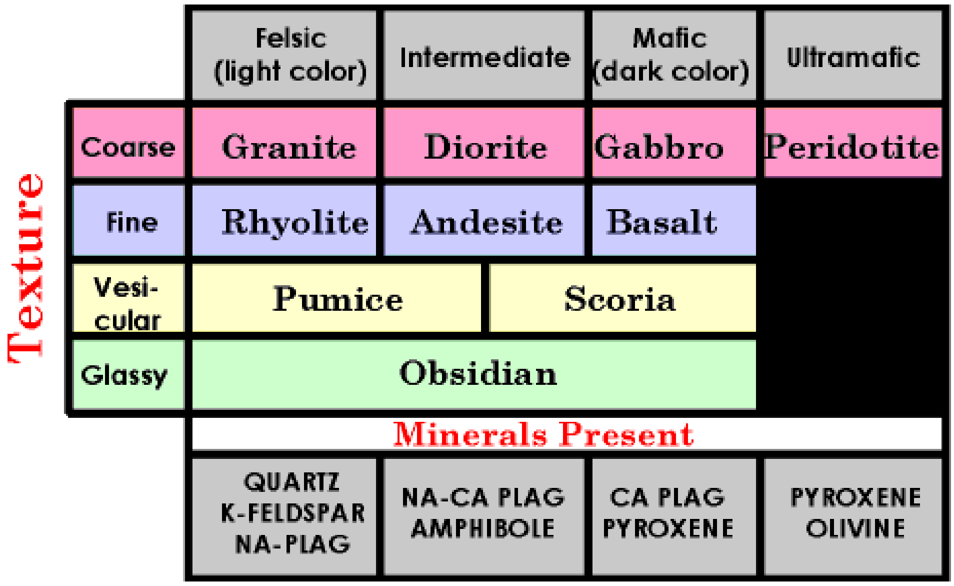
Coarse grained - Individual mineral grains can be seen which the naked eye. Rock must have cooled slowly to allow large crystals to develop.

Fine grained - Mineral grains are present but are two small to be seem with the eye. Cooled rapidly before crystals had a chance to grow.

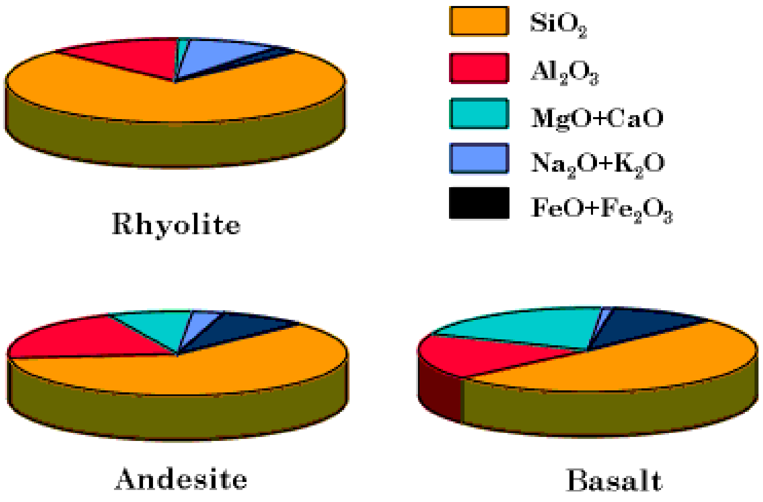
Vesicular - Rock containing vesicles (gas holes). Always light weight. Example pumice.

Glassy - Not composed of minerals at all but a true glass. Glasses are <u>not</u> crystalline!

All typical classification schemes rely on a combination of texture, particularly grain size, and mineralogy. But, keep in mind they are process-oriented. Coarse grained are plutonic, fine grained are volcanic. See **Figure** below that depicts a typical classification. Stress similar mineralogy of granite vs. rhyolite, just differ in grain size. Compare granite to gabbro which have the same grain size, but different mineralogy. Notice from **figure** how the three comon fine-grained rocks, rhyolite, andesite and basalt differ in their chemistry. Rhyolite is very rich in silica while basalt has less silica, but more iron and magnesium. Andesite is intermediate.



Texture	Felsic (light color)	Intermediate	Mafic (dark color)	Ultramafic
Coarse	Granite	Diorite	Gabbro	Peridotite
Fine	Rhyolite	Andesite	Basalt	
Vesi-cular	Pumice		Scoria	
Glassy	Obsidian			
	Minerals Present			
	QUARTZ K-FELDSPAR NA-PLAG	NA-CA PLAG AMPHIBOLE	CA PLAG PYROXENE	PYROXENE OLIVINE



Volcanoes

Volcano - Cone shaped feature with a pit or depression at the summit.

Crater - The pit or depression at the top of the volcano.

Caldera - A destructive feature that marks the site of collapse of a volcano's summit. Form when magma chamber beneath the volcano is emptied.

Anatomy of a Volcanic Eruption

1. Magma is generated at depth. Cause of magma generation is a combination of factors including; geothermal gradient, radioactive heating and friction along plate boundaries. Temperature of typical magma 600-1400 degrees C. Depth of generation 50-100 km based on geophysics.
2. Because magma is less dense it begins to rise. Lithostatic pressure drops as magma rises and it begins to boil. This releases gas which exerts outward pressure.
3. At depth of 3-5 km magma reaches gravitational equilibrium. Boiling continues. If outward pressure of gas exceeds lithostatic pressure an eruption occurs. Obviously greater the volatile content (water) the more potential for a destructive eruption we have. Viscosity of the magma also an important consideration.

Products of Volcanic Eruptions

Lava - Magma which flows on the surface

1. Pahoehoe - Ropy, fast moving low viscosity lavas
2. AA - Blocky, slow moving higher viscosity lava

Pyroclastics - Airborne material

1. Dust - Fine fragments carried into upper atmosphere. Can remain suspended for weeks or years.
2. Ash - Fragments of angular glass <.5 cm in diameter
3. Cinders - Slag sized fragments .5-2.5 cm in diameter
4. Lapilli - Fragments >2.5 cm
5. Blocks - Very large angular fragments
6. Bombs - Large rounded masses

Classification of Volcanoes

Morphology - appearance, size and shape

a. **Shield Volcano** - Built up by repeated lava eruptions from a central vent. Very large with broad, mound- shaped, sides. Slopes 5-10 degrees. Typical example is Kilauea. Few in number and in center of plates.
b. **Composite (stratovolcano)** Built from a combination of lave flows and pyroclastic material. Have smaller size, diameter 3-30kms and steeper slopes (10-30 degrees). Occur along plate margins. Many examples Vesuvius, Cascade volcanoes.
c. **Cinder Cone** - Small feature a few thousand meters in diameter or less with very steep sides (30-40 degrees). Very numerous. Example Paracutin in Mexico.

Distribution of Active Volcanoes - Most lie in a belt around the Pacific termed **Ring of Fire**. Also occur in Southern Europe, Atlantic, Central Africa.

Comparison of Mt. St. Helens and Kilauea

Mt. St. Helens	**Kilauea**
violent eruption	quiescent eruption
mostly pyroclastics	mostly lava
sticky viscous lavas	low viscosity lava
rhyolite	basalt
composite cone	shield volcano
at plate margins	center of a plate

Some Volcanic Eruptions

Vesuvius - 79 AD Was a dormant volcano called Mt. Somma. Erupted with no warning in August. Eruption was so sudden inhabitants of Pompeii and Herculeaneum were buried where they lie. Eruption was believed to be a **nuee ardente (fiery cloud)** traveling at velocities of 150-200 km/hr. Prior to 79 AD last eruption believed to have occurred about 10,000 BC when Mt. Somma was formed. 79 AD eruption blew top off Mt. Somma and cone of Vesuvius was born. Since that time periodic eruptions have occurred to the present. Initial history one of repeated violent pyroclastic explosions. Since 17th century we are in a period of quiet eruptions accompanied by lavas.

Mt.St. Helens - May 18, 1980. Eruption preceded by numerous of small earth tremors and steam venting. Last previous eruption was 1831. Summit blown off removing upper 400 m in one blast of rock and ash. One of a chain of volcanoes from southern B.C. into northern California (Cascade Range).

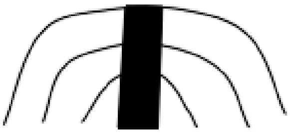
Hawaiian Islands - Part of a 2400 km long chain of volcanic islands stretching across the central Pacific. Oldest islands in the chain are the most heavily eroded and have the oldest rocks. Lie to the northwest. Youngest islands are still active and lie at the southeast end of the chain. Postulated that the islands overlie a mantle hot spot. Movement of the Pacific lithospheric plate to the northwest over the stationary hot spot has caused the observed relationships.

Iceland - *Fissure Eruptions* occur as lava flow from a long linear fissure rather than a central volcano. Seem to be associated with spreading centers at constructive plate margins. Erupted lavas consist of voluminous low viscosity basaltic lava.

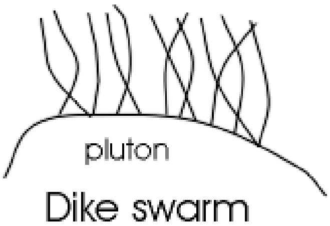
Intrusive Igneous Rocks

Pluton - Body of magma which has solidified beneath the earth. Classified based on whether they are **concordant** (i.e. they are parallel to layering of host) or **discordant** (cross cut host). Also if they are **tabular** (table-like) or **massive** (equi-dimensional football-shaped). (**Figure**)

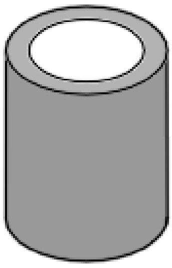
1. *Sill* - Tabular concordant pluton
2. *Dike* - Tabular discordant pluton
3. *Laccolith* - Massive concordant pluton
4. *Batholith* - Massive discordant pluton



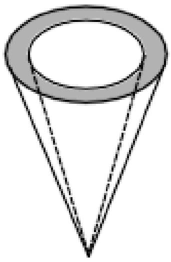
Plug



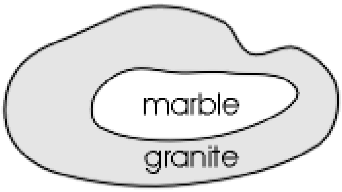
Dike swarm



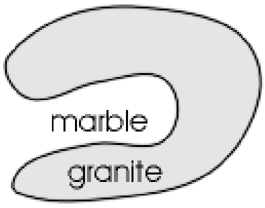
Ring dike



Cone sheet



Pendant



Septa

Magma Crystallization

By the end of the 19th century it was recognized that all igneous rocks formed from the crystallization of a magma. A fundamental question that followed was "why do we get so many different types of igneous rocks if we had one primordial starting material". Use the analogy of baking a cake. N.L. Bowen conducts the first systematic study of the crystallization of igneous rocks.

Publishes **Bowen's Reaction Series** (**Figure**) which shows that the minerals in igneous rocks crystallize in an orderly sequence. Discontinuous Series so named because as temperature falls we change from one new mineral to another (Ex. olivine alters to pyroxene). Continuous Series in which plagioclase feldspar merely changes composition from Ca-rich at high temperature to Na-rich at low temperature. Does not involve the formation of a new mineral, just a compositional change. This does not really help us understand why we have different igneous rocks, but it does seem to show that there is some order in nature. To more closely examine this order let's look only at the plagioclase feldspars. Why? Because plagioclase occurs in most igneous rocks. So if we can understand how and why feldspars form we may have some understanding about how different rocks form.

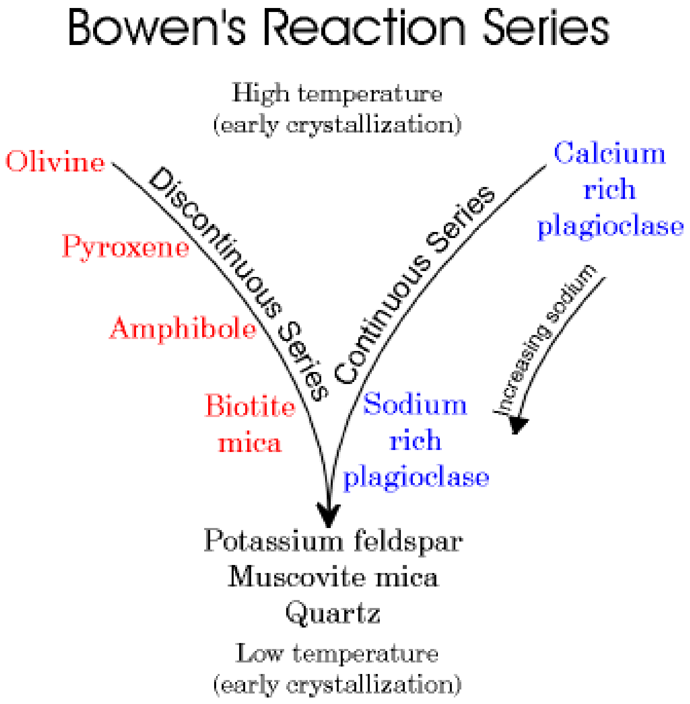
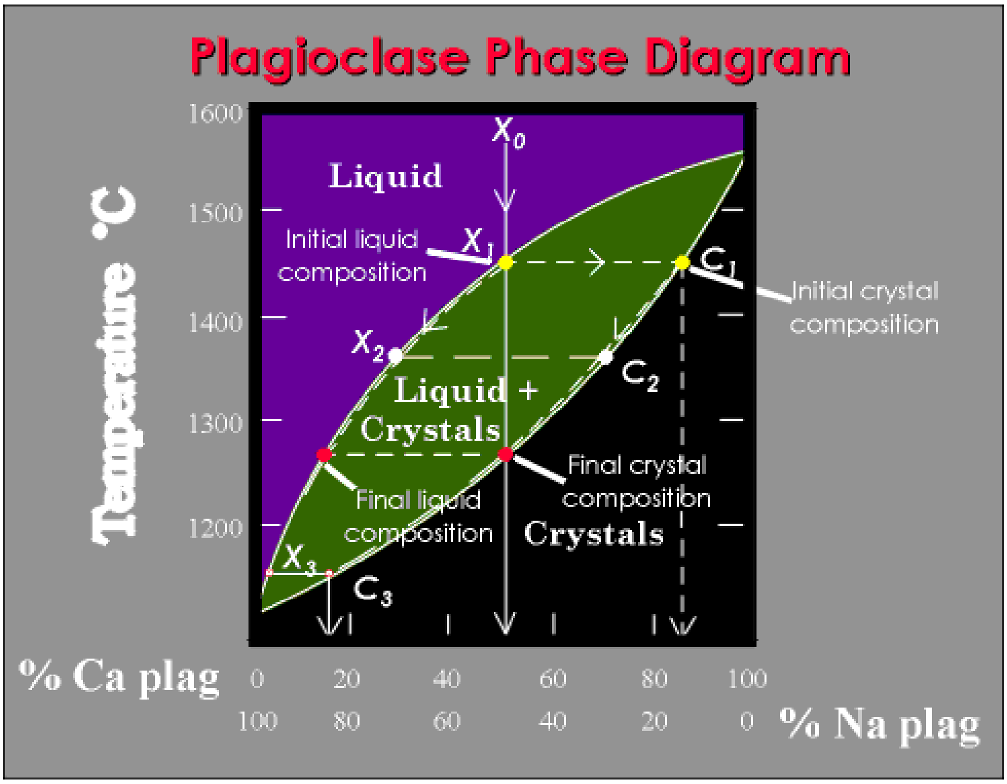
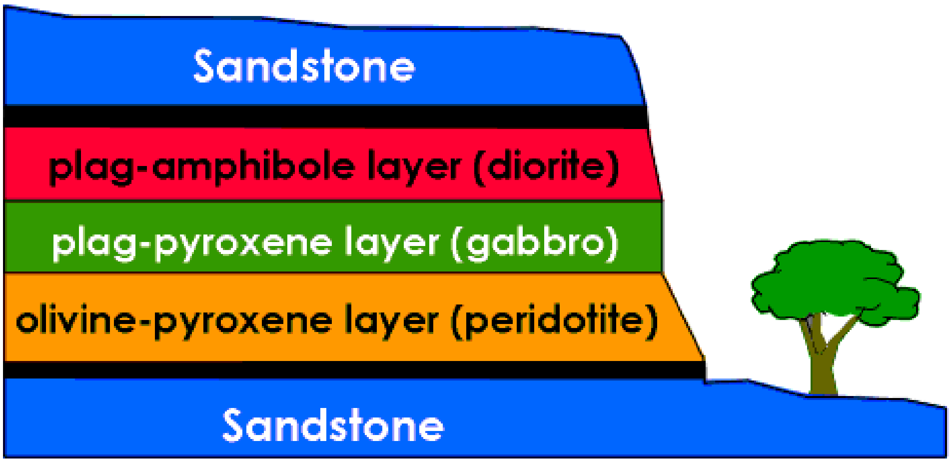


Figure (Phase Diagram for Plagioclase) Explain how the diagram works. Plot of temperature vs. composition. Upper line is **liquidus**. Separates *liquid* field from *liquid + crystals* field. Lower line is the **solidus** which separates the *liquid + crystals* field from the *solid* field. We can begin by examining the crystallization path of a liquid of composition X_0. It cools to temperature X_1 and at that point the first crystals begin to form. To determine their composition we project a horizontal line to the solidus and find they have the composition C_1 or about 85% Ca plag. As temperature continues to fall liquid composition shifts along liquidus to X_2 and solid crystals shift in composition along the solidus to C_2. At the completion of crystallization, (about 1275°C) the final solid has exactly the same composition as the starting liquid. **This is an example of equilibrium crystallization.**

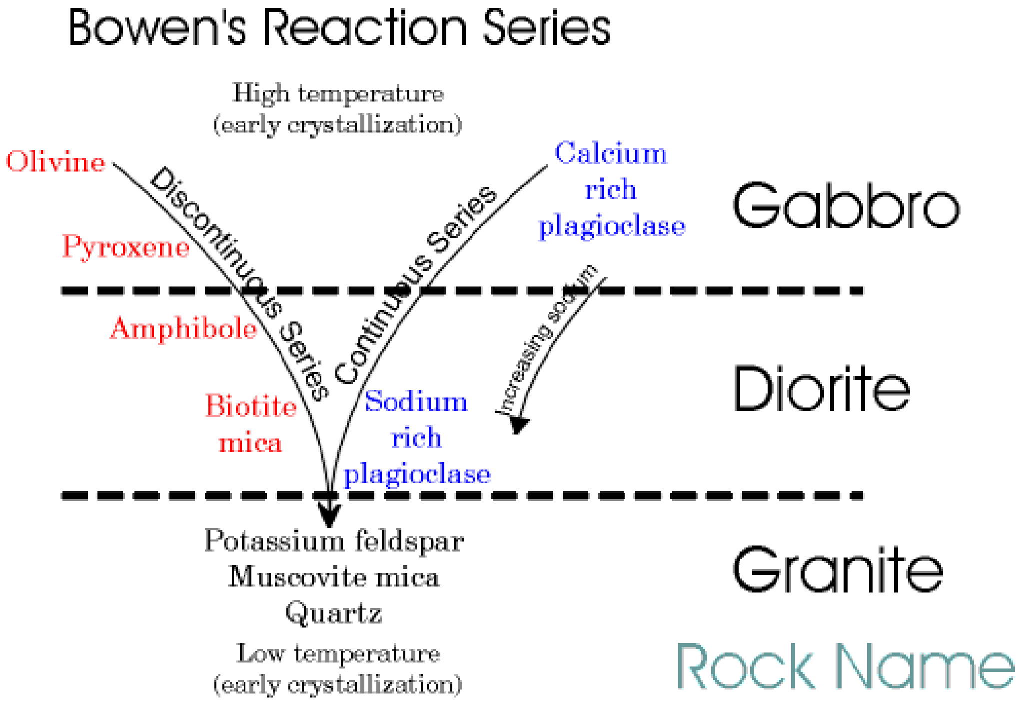


Now let's look at what happens when we remove some of the crystals from the liquid as they form rather than allowing them to remain in contact with the liquid and change composition as they did in the example above. Result would be a series of fractions of crystals of different composition (**Fractional Crystallization**).

Theoretically, fractional crystallization seems possible, but how could it occur in nature? By the process of **gravitative settling**, in which the early formed crystals in a magma sink to the bottom of the chamber due to their greater density and as such are shielded from reacting with the magma. Result is a series of layers of crystals of differing composition. Where can we find such a phenomenon in nature? **Figure** shows layering in the Palisades Sill that has occurred as the result of gravitative settling and fractional crystallization.



Return to Bowen's Reaction Series and show the result of plotting the various major igneous rocks on the diagram (**Figure**). We could form each of these rocks as the result of fractional crystallization. The problem with fractional crystallization, however, is that it is not very efficient. Even under the best of circumstances we can form only **5%** granite by fractional crystallization. Continents are **60%** granite so where did all of it come from? Answer is there must be another mechanism involved. Go back to Plagioclase Phase Diagram and look at what happens if we take a solid of 50% Na plagioclase and 50% Ca plagioclase and heat it just enough to **partially melt** the solid. Liquid that forms is very Na-rich. Because it is a liquid it rises out of the system, eventually to crystallize higher in the crust. The solid that forms has the very same Na-rich plagioclase as the composition of the liquid. Thus if we partially melt a solid we can generate a liquid of very different composition which eventually recrystallizes as a rock of very different composition. This mechanism of forming rocks of different composition is termed **Partial Melting** and is thought to be the dominant mode of formation of the various different rocks.



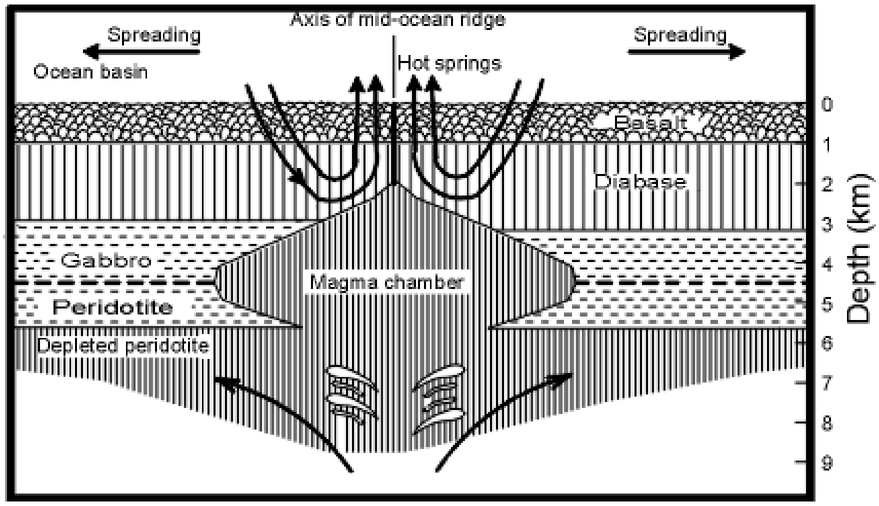
Partial melting leads to the following:

peridotite ---> basalt

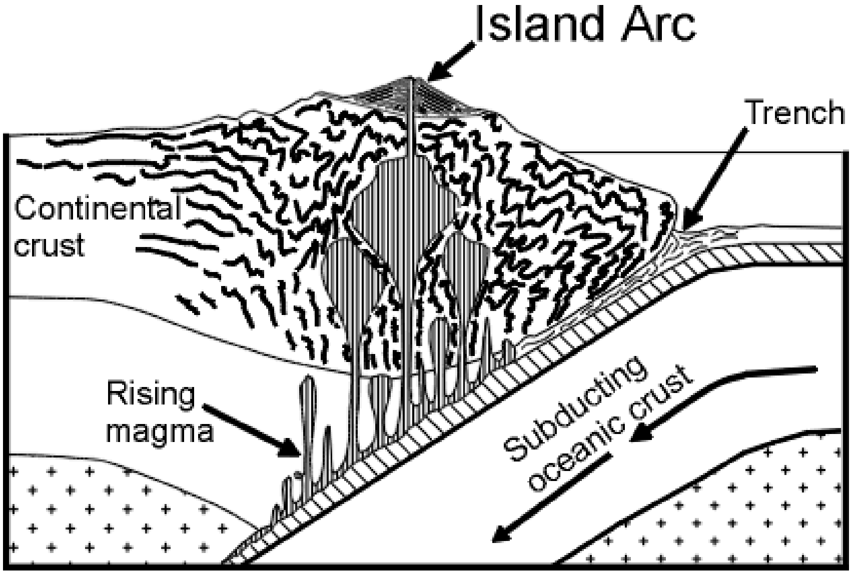
basalt ---> andesite

andesite --> granite (rhyolite)

Mantle of the earth thought to be peridotite. This conclusion ts based on the velocity of seismic waves and samples of peridotite found in diamond pipes. If we partially melt a peridotite (3-8%) the magma we generate has the composition of a basalt. **Figure** shows the typical result of partial melting of mantle peridotite at a divergent plate boundary such as the Mid- Atlantic Ridge. The crust is pulled apart and a basaltic magma is produced and then rises upward and emplaces itself on the sea floor as a pillow lava. Beneath the pillow lavas are diabase dikes, gabbro and peridotite.



The situation is different for the formation of granites at subduction zones. In order to form a partial melt at realistic depths we need water. This is because water dramatically **lowers** the melting point of rocks. The water comes from sediments carried down the subduction zone at convergent plate boundaries (**Figure**). Water lowers melting point of sediments and surrounding igneous rocks, thus forming a partial melt at 30-50km.



So the following occur:

At divergent plate boundaries peridotite mantle partially melts to give basalt magma.

At convergent plate boundaries water is carried down subduction zones causing partial melting and the formation of granitic magmas.

METAMORPHISM

Metamorphism - Solid state changes in sedimentary or igneous rocks. Takes place within the crust and in response to the agents of metamorphism.

Agents of Metamorphism

1) Heat

    a) frictional sliding of plates

    b) radioactivity

    c) gravitational compression

2) Pressure

    a) burial (lithostatic)

    b) directed pressure due to tectonism

3) Chemically Active Fluids

    a) Water - circulates in response to heat generated by cooling magmas. Exchanges ions between the solution and the rock through which it is traveling.

Types of Metamorphism

Dynamic metamorphism - Metamorphism along faults zones in response to pressure. Involves a brittle deformation of the rock during which it is ground into fine particles. Heat and chemical fluids are less important. Most important rock is **mylonite** a very distinctive lineated rock.

Contact metamorphism - Alteration of rocks at or near the contact of a cooling pluton. Most important agents of metamorphism are heat and circulating fluids. Pressures usually less important, often in the range from 1-3 kilobars. Temperatures 300-800 degrees C. Produces a series of zones characterized by the presence of one or more diagnostic minerals.

Regional metamorphism - Occurs over a very large area in response to increased temperature and pressure. Circulating fluids are unimportant due to the great depth of regional metamorphism. Pressure seals pore space in the rocks and fluids can't circulate. A variation on regional metamorphism is **burial metamorphism**, the latter occurs solely in response to burial. Generally, regional metamorphism occurs in tectonically active areas (i.e. plate margins).

Classification of Metamorphic Rocks

Process oriented classification just as is that for the igneous rocks. The two dominant processes are regional and contact metamorphism.

Foliated - Contain linear or planar features. Form in response to active pressure during regional metamorphism. Foliation is not to be confused with the original sedimentary layering.

Slate - Fine grained, with nice rock cleavage. Cleavage due to the parallel orientation of the mica grains.

Phyllite - Well developed foliation. Grains slightly larger than those of a slate. Again composed of mica. Poorer rock cleavage.

Schist - Contains grains that can be seen by the eye. Still has noticeable foliation. May be most common of all metamorphic rocks.

Gneiss - Consists of alternating light (feldspar-quartz) and dark (amphibole-biotite) bands. Requires a higher degree of metamorphism.

Non-foliated - Show no evidence of foliation and are apt to form in a contact metamorphic environment where pressure is unimportant.

Marble - Recrystallized limestone (calcite).

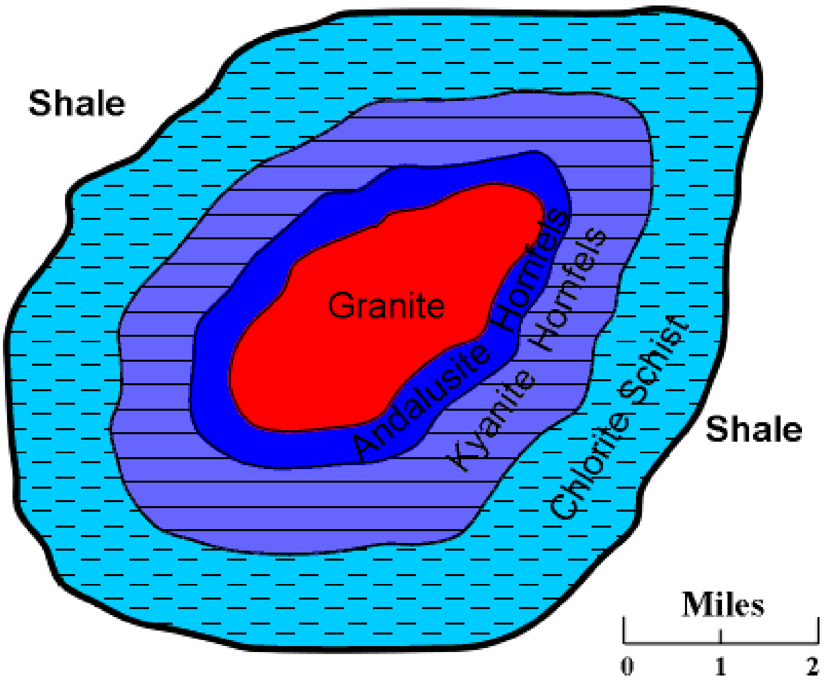
Quartzite - Metamorphosed quartz sandstone.

Hornfels - "Spotted rock" due to the presence of large crystals in a fine-grained matrix.

Contact Metamorphism

Metamorphic aureole - Zone characterized by a certain mineral or assemblage of minerals which differ from those originally present in the protolith (starting material). Index Mineral - The mineral that characterizes each contact metamorphic zone. Isograd - line on a map that marks the first appearance of that mineral.

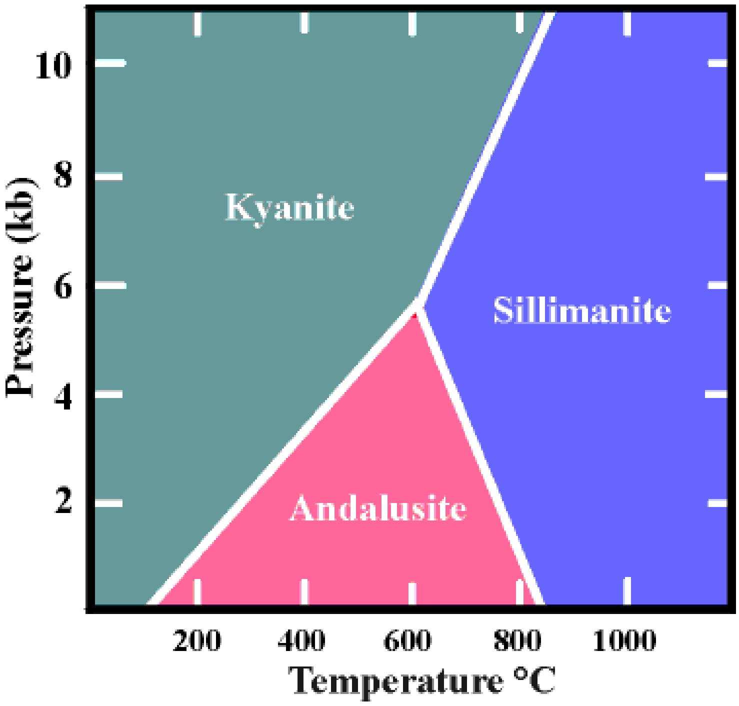
Figure: the Onawa Pluton in Maine. Note the various zones and index minerals. Several factors control this zoning.



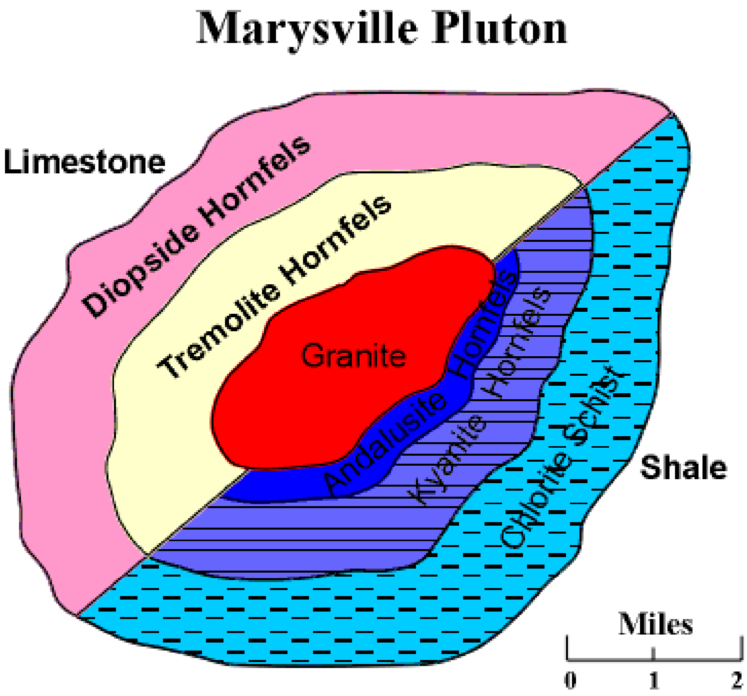
Onawa Pluton

- **Temperature**
- **Pressure** - not really important in contact metamorphism
- **Composition of the pluton** - it supplies the fluid

Look at phase diagram for the Al_2SiO_5 polymorphs (**Figure**) and notice how the zoning reflects the stability of the various mineral phases. Why is there no sillimanite zone in the Onawa pluton? Answer - it didn't get hot enough adjacent to the pluton.

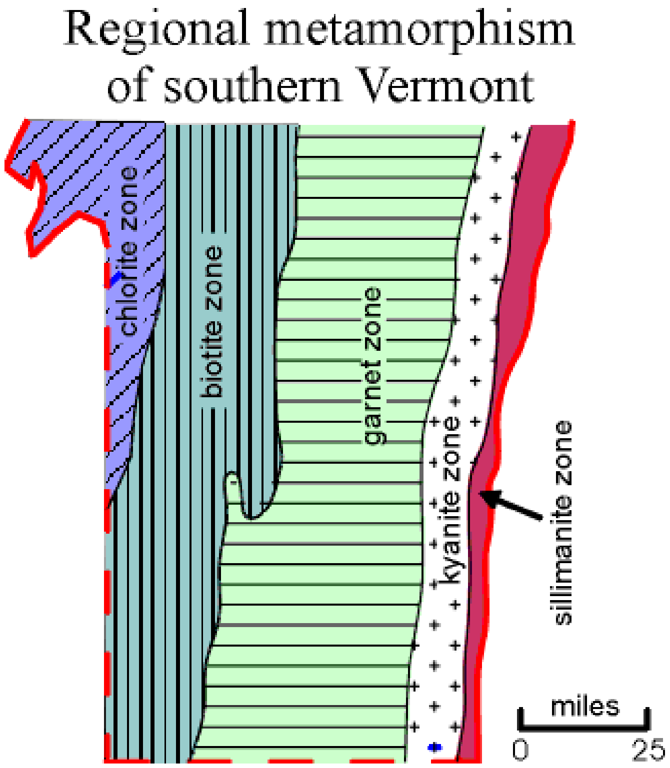


Look at the Marysville Pluton in Utah (**Figure**). What has happened here? Why is the zoning on the northwest side of the pluton different? What did we fail to take into consideration?



- **Composition of the starting material**

This creates a problem if a large area has undergone metamorphism as is the case in regional metamorphism. The chances that only a single rock type will be present over a wide area is small. Sometimes it works, such as in southern Vermont (**Figure**). Here we are looking at regional metamorphism of a single rock type, shale.



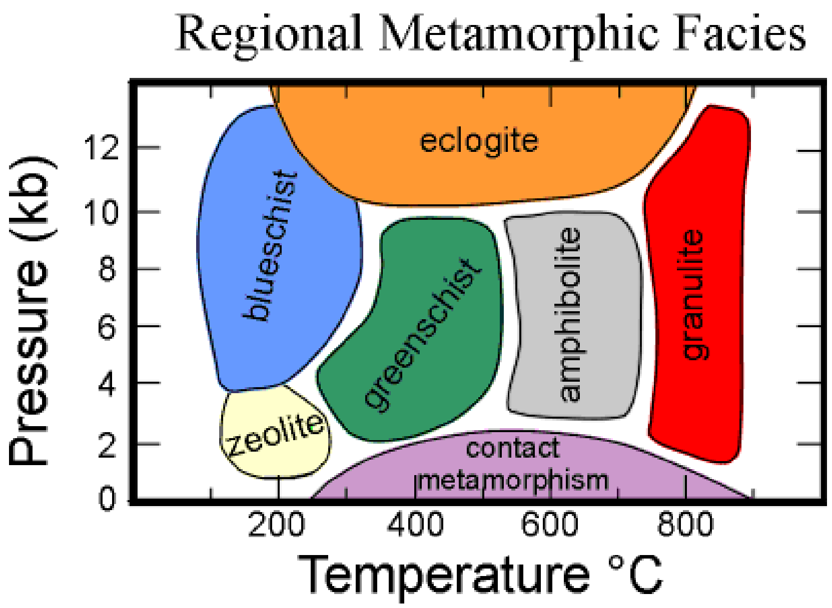
Regional Metamorphism

To attack complex regional metamorphism we obviously needed a different approach since index minerals often will not work. There would be one for each different starting rock type and the result would be so complex it would be difficult to interpret.

Characteristics of regional metamorphism:

1. Occurs over large areas (1000's of sq. miles)
2. Closely related to episodes of mountain building
3. Both temperature and pressure important

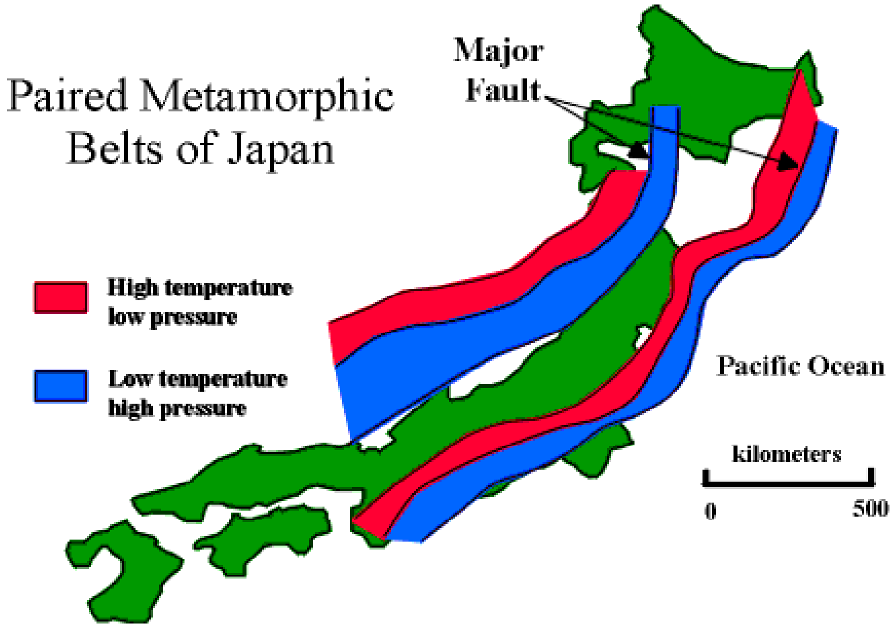
Metamorphic facies - An assemblage of minerals that reached equilibrium under a specific set of temperature and pressure conditions. Each facies named for a readily recognizable characteristic mineral or other feature. Remember that any one mineral does not have to be present, the facies is characterized by several different minerals (**Figure**).



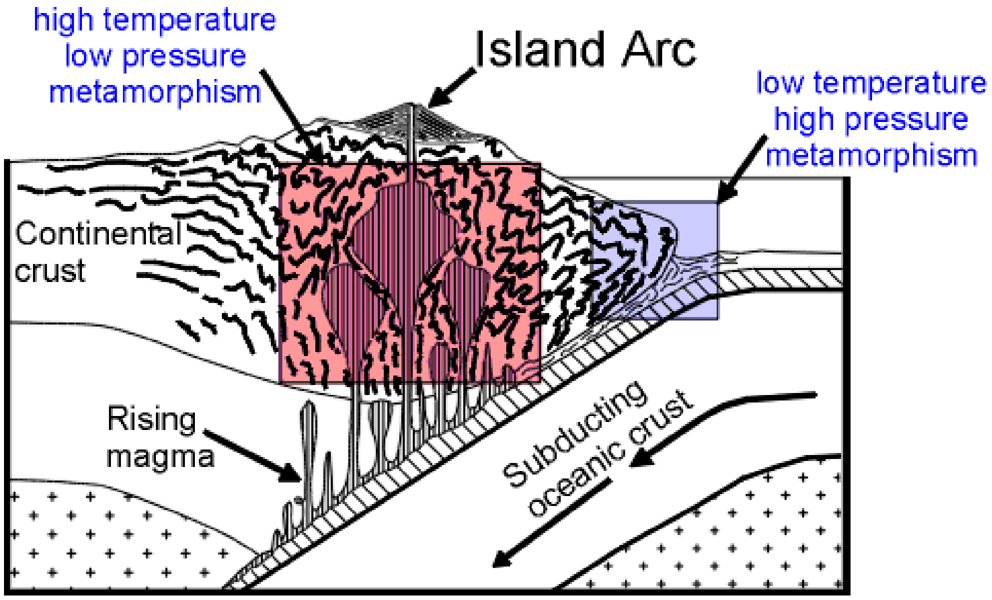
1. Zeolite - Transitional from sedimentary conditions. P 2-4 kb and T 200-300 degrees C.
2. Greenschist - Low temperature and pressure facies of regional metamorphism. P 3-8 kb and T 300-500 degrees C. Characterized by the green minerals chlorite, epidote and actinolite.
3. Amphibolite - Moderate to high temperature and low pressure regional metamorphic facies. P 3-8 kb and T 500-700 degrees C. Characterized by the presence of amphibole.
4. Granulite - High temperature and low to moderate pressure regional metamorphic facies. P 3-12 kb and T >650 degrees C. Characterized by quartz, feldspar, same minerals in a granite, hence the name.
5. Blueschist - Low temperature and high pressure metamorphic facies. Occurs only in areas of abnormally low geothermal gradients. P >4 kb and T 200-450 degrees C. Name from the blue mineral glaucophane. Common rock type on Catalina Island. Actually very rare in much of the world.
6. Eclogite - Mantle rock, probably not a valid metamorphic facies. Requires P >10 kb and T from 350-750 degrees C.

Myoshira and the "Paired Metamorphic Belts" of Japan

Figure shows Myoshira's geologic map of Japan. Published in the early 1960's. Shows a series of paired belts with a low temperature, high pressure belt (oceanward) juxtaposed against a high temperature, low pressure belt (landward). This presented problems to geologists. What was this map showing>



(**Figure**) Myoshira was actually mapping the location of ancient subduction zones. High P low T belt marked the trench where plates were colliding, hence high pressure. Low temperature due to the cooling effect of seawater. Landward the rising plutons from the zone of partial melting caused the local high temperatures at relatively shallow depth. Oceanward facies is the blueschist and landward a combination amphibolite and granulite.



WEATHERING AND SEDIMENTARY ROCKS

Weathering - Process which acts at the earth's surface to decompose and breakdown rocks.

Erosion - The movement of weathered material from the site of weathering. Primary agent is gravity, but gravity acts in concert with running water.

Types of Weathering

1. *Mechanical or Physical* - the breakdown of rock material into smaller and smaller pieces with no change in the chemical composition of the weathered material.
2. *Chemical* - the breakdown of rocks by chemical agents. Obviously the chief chemical agent is water which carries dissociated carbonic acid.

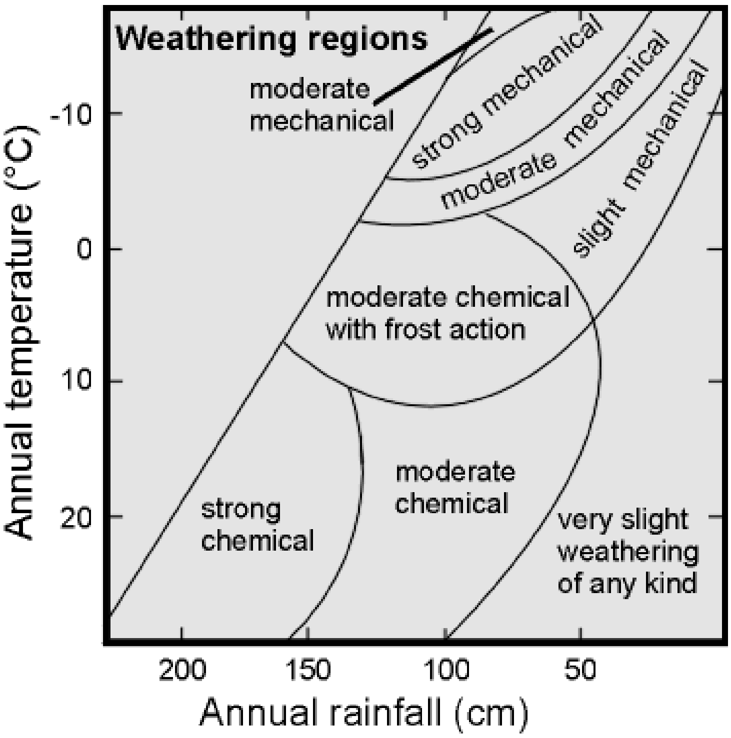
Mechanical Weathering

1. **Expansion and Contraction -** the thermal heating and cooling of rocks causing expansion and contraction.
2. **Frost Action -** Water freezes at night and expands because the solid occupies greater volume. Action wedges the rocks apart. Requires adequate supply of moisture; moisture must be able to enter rock or soil; and temperature must move back and forth over freezing point.
3. **Exfoliation -** process in which curved plates of rock are stripped from a larger rock mass. Example Half Dome. Exact mechanism uncertain but probably due to unloading.
4. **Other types -** Cracking of rocks by plant roots and burrowing animals.

Chemical Weathering

Factors which effect the rate of chemical weathering are:

- Particle size - Smaller the particle size the greater the surface area and hence the more rapid the weathering
- Composition
- Climate **(See Figure)**
- Type and amount of vegetation



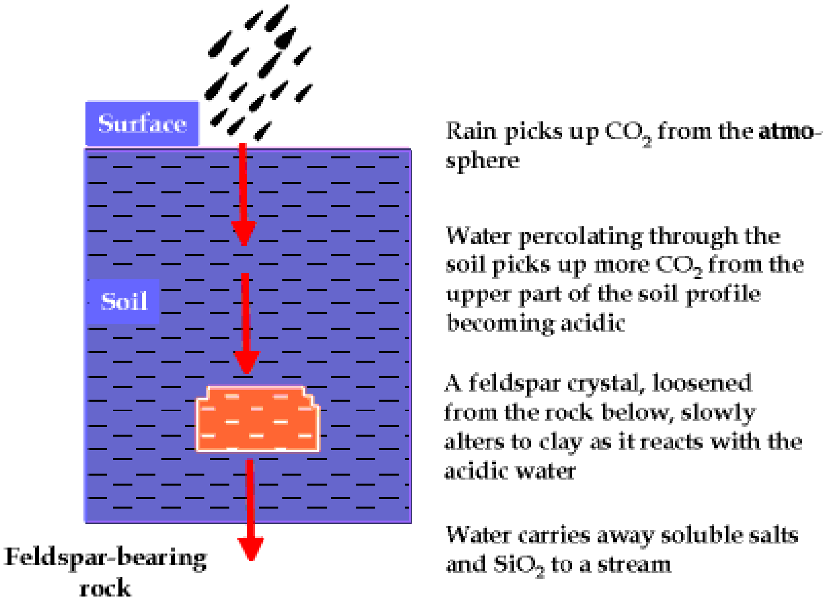
Chemical Weathering of Rocks

Show **Figure** and explain formation of carbonic acid

$$H_2O + CO_2 \text{ -------}>> H_2CO_3$$

Acid then dissociates and the following happens:

$$2KAlSi_3O_8 \text{ (feldspar)} + 2H^+ + H_2O \text{ -------}>> Al_2Si_2O_5(OH)_4 \text{ (clay)} + 2K^+ + 4SiO_2$$



Rain picks up CO_2 from the atmosphere

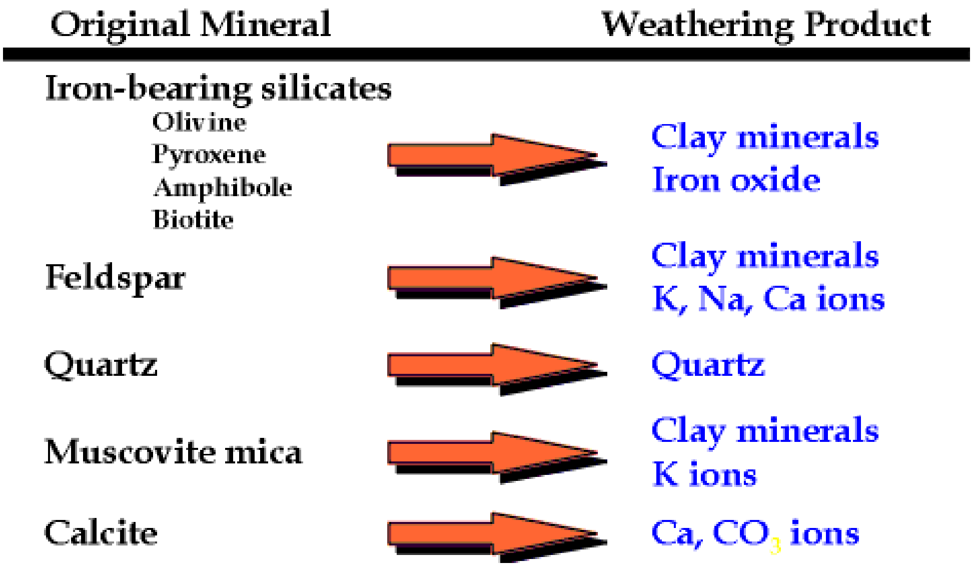
Water percolating through the soil picks up more CO_2 from the upper part of the soil profile becoming acidic

A feldspar crystal, loosened from the rock below, slowly alters to clay as it reacts with the acidic water

Water carries away soluble salts and SiO_2 to a stream

Weathering of Igneous Minerals

Products of Weathering **Figure**:



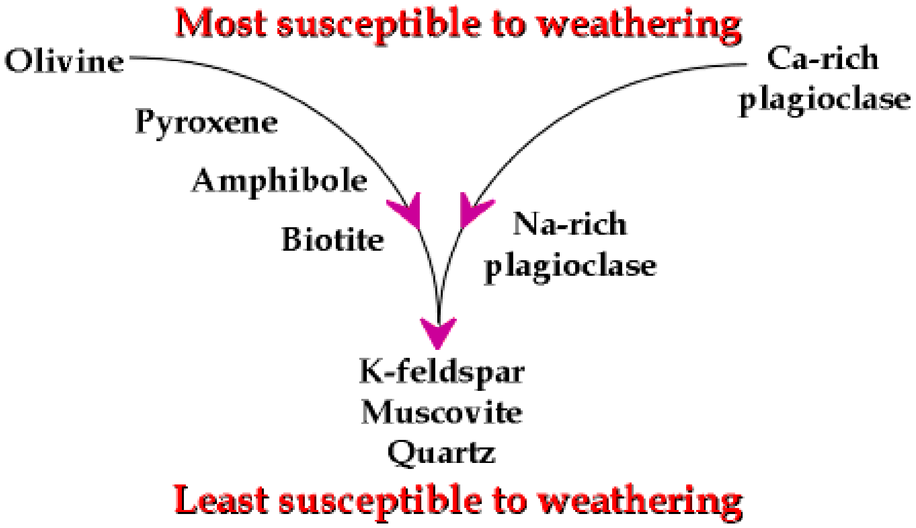
Original Mineral	Weathering Product
Iron-bearing silicates Olivine Pyroxene Amphibole Biotite	Clay minerals Iron oxide
Feldspar	Clay minerals K, Na, Ca ions
Quartz	Quartz
Muscovite mica	Clay minerals K ions
Calcite	Ca, CO_3 ions

1. Quartz - slow process and largely ineffective. Quartz remains quartz. Grains are rounded.
2. Feldspar - weathers to clay with the cations Na, Ca, and K going into solution. Clays that can form include kaolinite (pure aluminum silicate), illite and montmorillonite. Factors which dictate clay formation are (a) climate; (b) time; (c) parent material.

3. Muscovite - Same as above
4. Ferromagnesian minerals - weather to clay plus highly insoluble iron oxides, essentially varieties of limonite (rust).

Rates of Weathering

Studied by S.S. Goldich (**Figure**) and found to be inverse of Bowen's Reaction Series. Why? A function of equilibrium, the higher the temperature of formation of a mineral the more unstable it is at the earth's surface. Hence olivine weathers the most rapidly.



Soils

Soil - Surficial material that forms due to weathering. Includes an organic component. Many different soil types. Factors effecting their formation are:

1) Climate

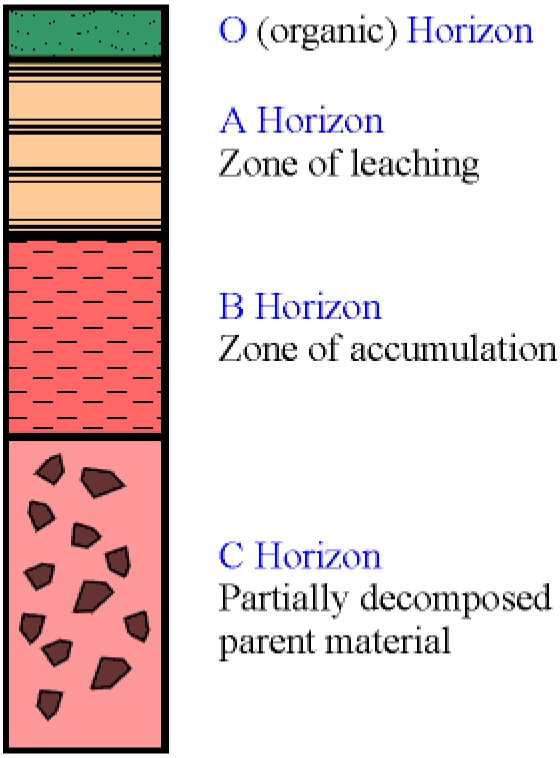
2) Relief

3) Bedrock material

4) Time

Classification of soils varies depending on the classifier. Geologists use a very simple classification based largely on materials added or removed from the soil during its formation.

Soil consists of four major zones (horizons) (**Figure**).



1. *O horizon* - **Organic layer**

2. *A horizon* - **Zone of leaching** - Cations are leached from this horizon by strongly acid solutions generated in the O horizon

3. *B horizon* - **Zone of Accumulation** - Cations leached out of the A horizon accumulate here. Horizon consists of clays, iron and aluminum oxides. Deposition due to neutralization of acid solutions.

4. *C horizon* - Partially decomposed parent material. Lower most zone.

Soil Types

Pedalfer - Named for the abundance of Al and Fe in the B horizon. Occur in temperate, humid climates. Lie generally east of the Mississippi River, correspond with 63 cm/yr rainfall contour.

Pedocal - Named for the accumulation of calcium carbonate in the B horizon. Characteristic of temperate, dry climates. Lie generally west of Miss River. Poorly developed A horizon, B horizon is caliche (calcium carbonate).

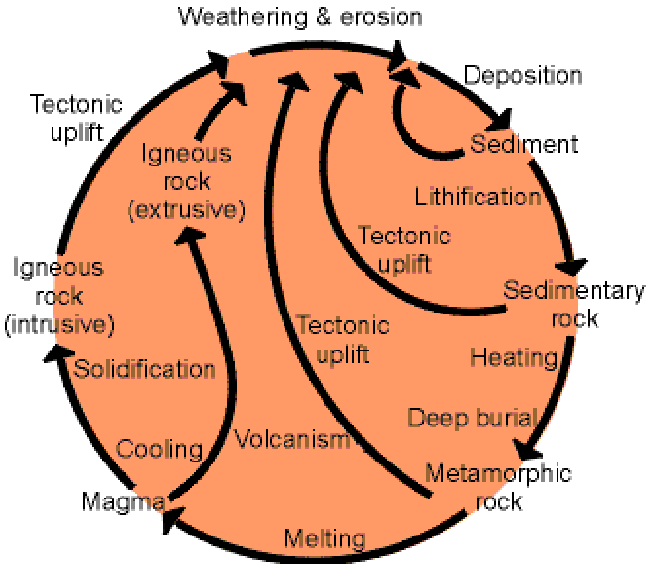
Laterites - Tropical soils thought to represent the end products of weathering. Characterized by stark red color and abundance of iron and aluminum oxides and lesser clay minerals. Requires abundant rainfall.

SEDIMENTARY ROCKS

Sedimentary Rocks - Layered or stratified rocks formed at or near the earth's surface in response to the processes of weathering, erosion, transportation and deposition.

Rock Cycle

All rocks discussed in this class are a part of the rock cycle (**Figure**).



Sedimentary Cycle (Figure)

Processes

1. **Transportation** - Transporting medium usually water. More rarely wind or glacial ice.
2. **Deposition** - Occurs when energy necessary to transport particles is no longer available. Deposition due to the gentle settling of mineral grains. Can also be result of chemical precipitation due to changing conditions.

3. **Lithification -** Involves several steps. All taken together are termed *Diagenesis*.

    a. Compaction - Squeezing out of water.
    b. Cementation - Precipitation of chemical cement from trapped water and circulating water.
    c. Recrystallization - Growth of grains in response to new equilibrium conditions

Single most important characteristic of sedimentary rocks is layering. Occurs in response to changes in conditions at the site of deposition. Sedimentary rocks cover **75%** of the earth's surface, but amount to only **5%** of the outer 10 km.

Origin of Sedimentary Material

- Derived directly from pre-existing rocks. Ex. quartz.
- Derived from weathered products of these rocks. Ex. clay.
- Produced by chemical precipitation. Ex. calcite.

First two processes result in detrital or clastic rocks. Third produces nondetrital or chemical sedimentary rocks.

Minerals of Sedimentary Rocks

1. Clay - Important constituent of mudstones and shales, but occurs in minor amounts in all sedimentary rocks.
2. Quartz - Most abundant constituent of sandstone. In addition to detrital quartz, free silica can be chemically precipitated as opal, chalcedony and chert.
3. Calcite - Chief constituent of limestone. Precipitates from seawater which is saturated in both Ca^{+2} and CO_3-2. Small changes in both T and P enough to cause precipitation. Differs from most compounds in that solubility decreases with increasing temperature.
4. Others

    a. Dolomite $CaMg(CO_3)_2$ - Most important constituent of dolostone
    b. Feldspars - Occur in sedimentary rocks formed by very quick deposition and burial allowing no time for feldspars to alter to clay.
    c. Iron oxides and sulfides - Chemical precipitates dictated by the environment at the site of deposition.
    d. Salts and gypsum - Chemical precipitates occurring in restricted sedimentary basins under arid climatic conditions. Modern analog is the Middle East (Red Sea).
    e. Volcanic Debris - Glass and other pyroclastic material incorporated into sediments.

5. Organic Material - Forms coal and gives color to black shales.

Classification of Sedimentary Rocks

Texture - Size, shape and arrangement of particles.

1. ***Clastic*** - Formed from broken or fragmented grains (**detrital**). Rock appears grainy. Basis of classification of the clastic rocks is the Wentworth Size Scale which was derived from studies of grain diameters.

Wentworth Size Scale		
Boulder	>256 mm	Conglomerate
Cobble	64-256 mm	
Pebble	2-64 mm	
Sand	1/16-2 mm	Sandstone
Silt	1/256-1/16 mm	Siltstone
Clay	<1/256 mm	Shale

Conglomerate - Detrital rock made up of more or less rounded fragments, an appreciable percentage of which are pebble size or larger

Sandstone - Consists primarily of grains in the sand size range. Dominant mineral in sandstones is always quartz. Further subdivide sandstones based on other minerals present. *Quartz sandstone* is 99% quartz. *Arkose* contains both quartz and feldspar. *Graywacke* is a garbage sandstone with quartz, feldspar, mica and rock fragments. Often has a significant fine-grained component and is poorly sorted.

Siltstone - Rare sedimentary rock composed mostly of silt sized particles. Rare because dominant mineral is quartz which does not like to get any smaller than sand size. Many siltstones thought to form by glacial grinding of sand-sized quartz grains.

Shale - Most common of the sedimentary rocks. Composed primarily of clay minerals. Often tends to split into flat sheets due to the mica-like cleavage of clay minerals.

2. ***Nonclastic*** (chemical) - Grains are interlocked through crystallization. Has igneous appearing texture with very little open space.

Limestone - Formed by the precipitation of calcite from seawater. Most form in marine environments, but also around hot springs, as a crust in desert soils, and as cave formation.

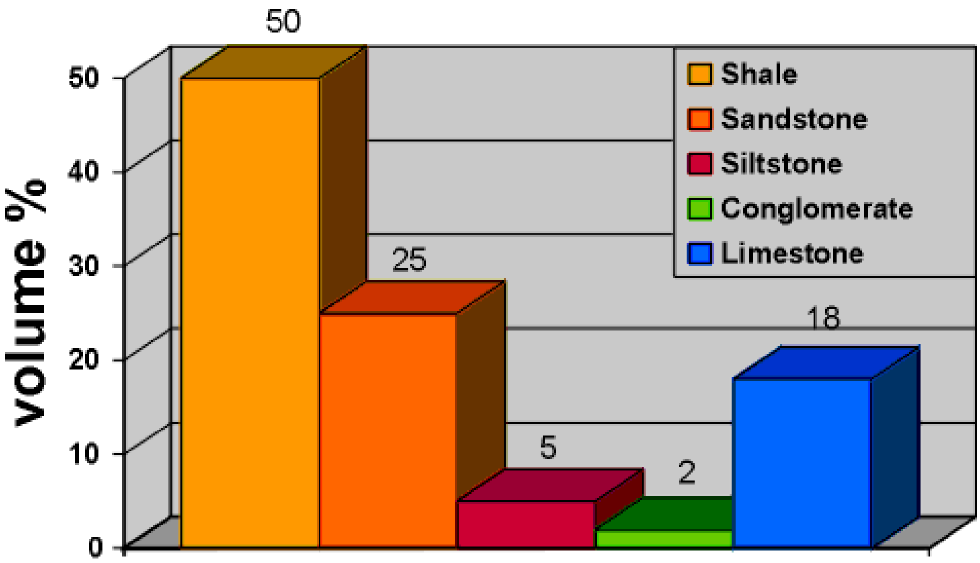
Dolostone - Composed of the mineral dolomite. Probably starts life as limestone then is altered to dolostone by Mg-bearing solutions in arid environments.

Evaporites - Formed by partial to complete evaporation of seawater in enclosed basins. Forms salts and gypsum.

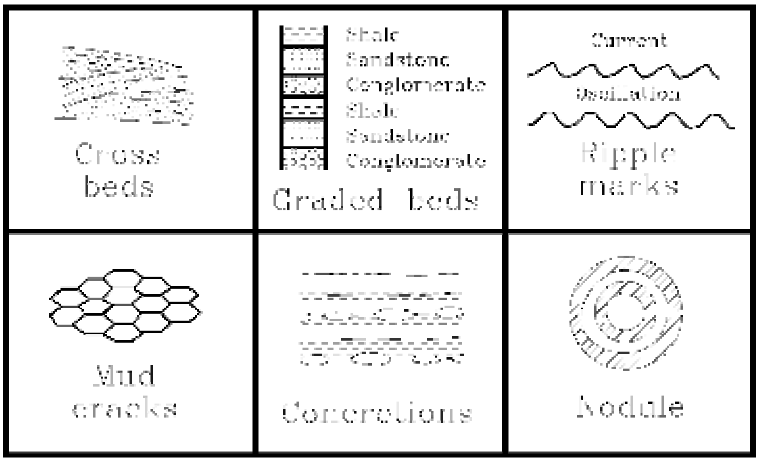
Organic Rocks - Rocks formed by the accumulation of organic material. Ex. coquina and chalk.

Coal - Rock composed of lithified plant material.

Abundance of Sedimentary Rocks ***(Figure)***



Sedimentary Structures ***(Figure)***



A) Structures formed during deposition

1. *Bedding* - Layering of sedimentary rocks. Each bed represents a homogeneous set of conditions of sedimentation. New beds indicate new conditions. Most layering is parallel, but occasionally it is inclined. These inclined layers are **cross beds**. Examples of sedimentary environments in which cross beds form are dune fields and deltas.
2. *Graded beds* occur when a mass of sediment is deposited rapidly. The bedding has the coarsest sediment at the bottom and finest at the top. Often found forming in submarine canyons. A collection of graded beds is termed a turbidite deposit. Well exposed in many of the sea cliffs along So. Cal. beaches.
3. *Ripple Marks* - Waves of sand often seen on a beach at low tide and in stream beds.

    a) Current - asymmetrical - Rivers

    b) Oscillation - symmetrical - Beaches

4. *Mud Cracks* - Polygonal-shaped cracks which develop in fine grained sediments as they dry out. Common in arid environments, such as a desert.

B) Structures formed after deposition

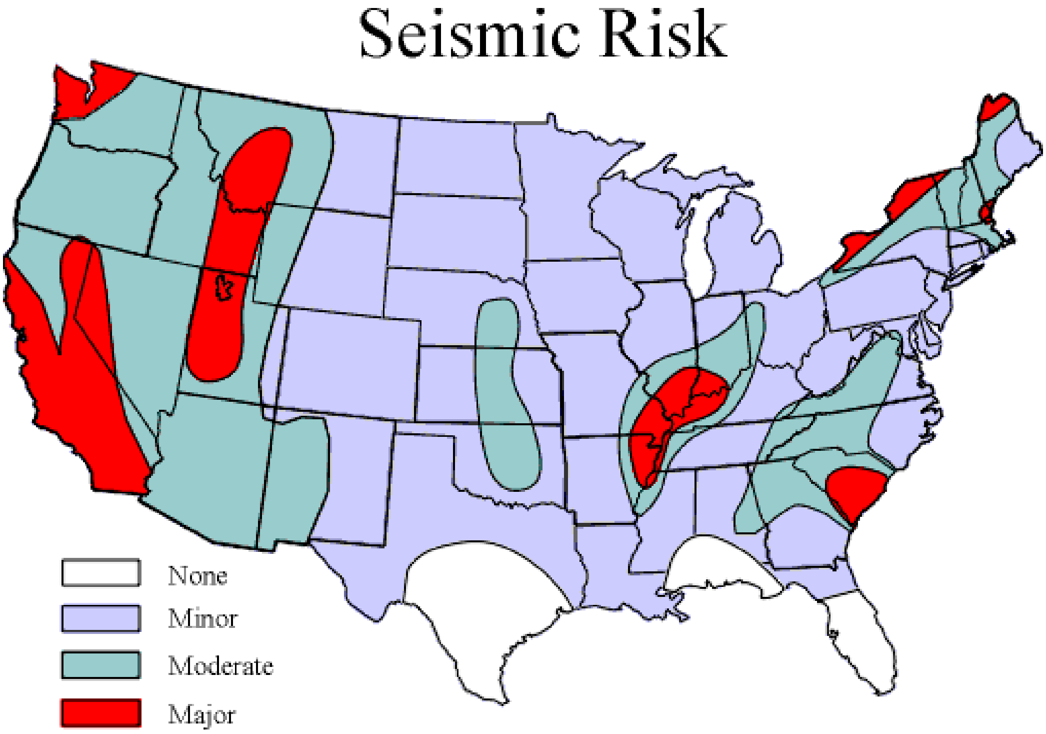
1. Nodule - Irregular, ovoid concentration of mineral matter that differs in composition from the surrounding sedimentary rock. Long axis of the nodule usually parallels the bedding plane and seems to prefer certain layers.
2. Concretion - Local concentration of cementing material. Generally round. Usually consist of calcite, iron oxide or silica. Can exceed 1 meter in diameter. Not understood how they form.
3. Geode - Roughly spherical structures up to 30 cm in diameter. Outer layer consists of chalcedony. Inside lined with crystals. Calcite and quartz the most common.

C) Other features

1. Fossils - Any direct evidence of past life. Examples are dinosaur bones, shells of marine organisms, plant impressions, etc.

EARTHQUAKES

Figure shows the maximum intensity earthquake which can occur and indicates that most of California is at extreme risk. Not shown is the frequency of large magnitude earthquakes, which for California is higher than anywhere else in the nation. Thus we must be earthquake aware since we are at great risk in southern California.



Tectonism - Forces working to distort the earth's crust. Rocks are deposited in originally horizontal layers. When we see them uplifted frequently they are highly contorted or deformed and no longer in horizontal layers.

Basic Types of Earth Movement

1. **Abrupt Movement** - Earthquakes accompanied by measurable uplift or depression of the earth's surface. Generally only a few meters, but occurs in a matter of seconds. Alaskan earthquake caused uplift of as much as 10-15 meters in a few seconds.
    a. **Vertical Displacement** - Upward or downward movement of rock masses. Classic example is Sagami Bay, Japan where all historic earthquakes can be correlated in the cliffs along the bay, because each was accompanied by vertical displacement.
    b. **Horizontal Displacement** - San Andreas Fault, 1000 km long reaching from offshore north of San Francisco to the Gulf of California. Characterized by horizontal displacement of in excess of 100 km over the

last 10-20 million years. Movement from a single earthquake can be as much as 10 meters.

2. **Slow Movement -** Creep in which the fault moves slowly and continuously over a long period of time. Average rate of movement of the central portion of the San Andreas is .5- 2 cm/yr.

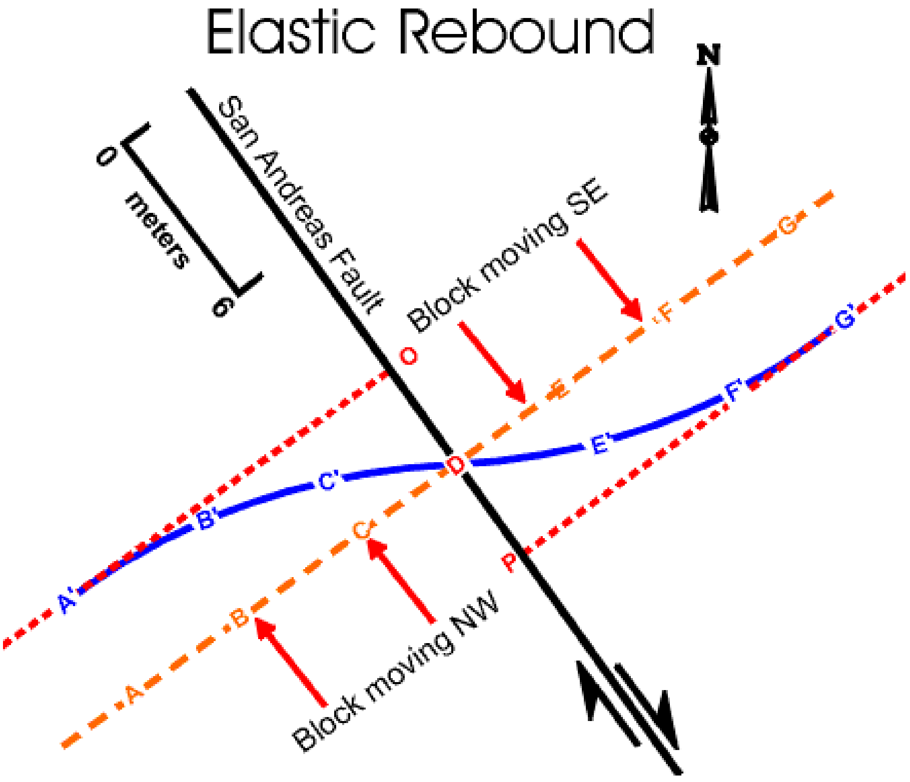
Seismology - The study of earthquakes. Recent science, developed only 80 years ago as a consequence of the 1906 San Francisco quake.

Earthquakes are dangerous because they:

1. cause structural damage due to the shaking motion;
2. cause fires due to broken gas mains;
3. sometimes generate tsumanis (seismic sea waves);
4. can trigger landslides;
5. cause cracks in the ground. A particular problem in Tokyo where Godzilla then runs rampant destroying the city.

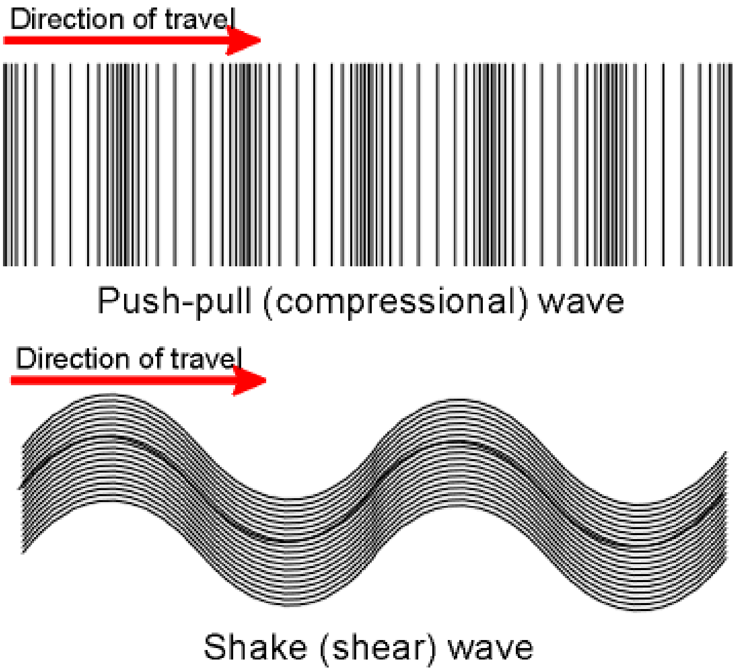
Causes of Earthquakes

Elastic Rebound - (**Figure**) Rock is stretched to the breaking point by twisting action on either side of the fault. Finally it can stand the strain no longer and it snaps causing displacements along the fault.



Earthquake Waves

1. Body Waves (**Figure**)- Waves moving through the body of the earth



   a. Push-Pull, Primary *(P)* Waves - Compressional waves moving parallel to the direction of propagation. Can move through solids, liquids or gas.
   b. Shake, Secondary *(S)* Waves - Shear waves traveling or advancing at right angles to the direction of movement. Travel only through solids.
2. Surface *(L)* Waves - Waves Similar to ripples on a pond

Interpreting Earthquakes

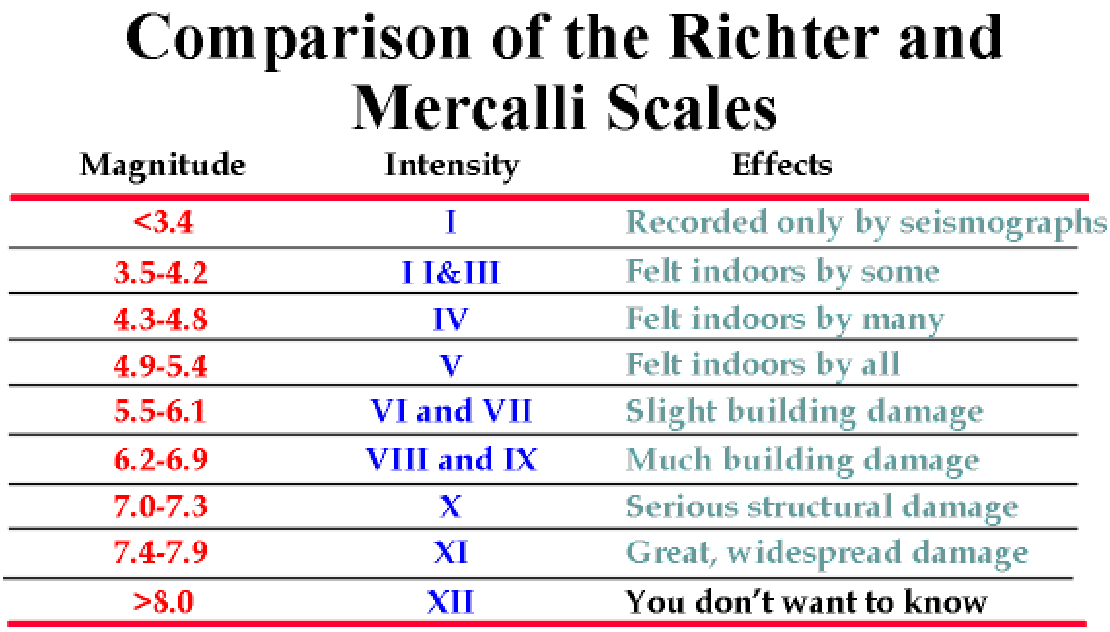
Focus (hypocenter)- Point at which earthquake originates.

Epicenter - Point on the earth's surface directly above the focus.

Scales of Earthquake Intensity/Magnitude ***(Table)***

1. ***Modified Mercalli*** - *Based on personal interviews of victims in the quake area. Has XII degrees of intensity.*
2. ***Richter Scale*** - *Based on the magnitude of energy released during a quake as measured by a seismograph (Describe how a seismograph works). Richter scale corrects for distance of the recording device from the epicenter. Scale is logarithmic so each increase by 1 represents a ten-fold increase in magnitude and actually a 30-fold increase in the amount of energy released. Largest quake ever*

recorded subject of some debate, but is either Alaskan (1964) at 9.2 or one in South America (1976) which may have been near 9.5.



Comparison of the Richter and Mercalli Scales

Magnitude	Intensity	Effects
<3.4	I	Recorded only by seismographs
3.5-4.2	I I&III	Felt indoors by some
4.3-4.8	IV	Felt indoors by many
4.9-5.4	V	Felt indoors by all
5.5-6.1	VI and VII	Slight building damage
6.2-6.9	VIII and IX	Much building damage
7.0-7.3	X	Serious structural damage
7.4-7.9	XI	Great, widespread damage
>8.0	XII	You don't want to know

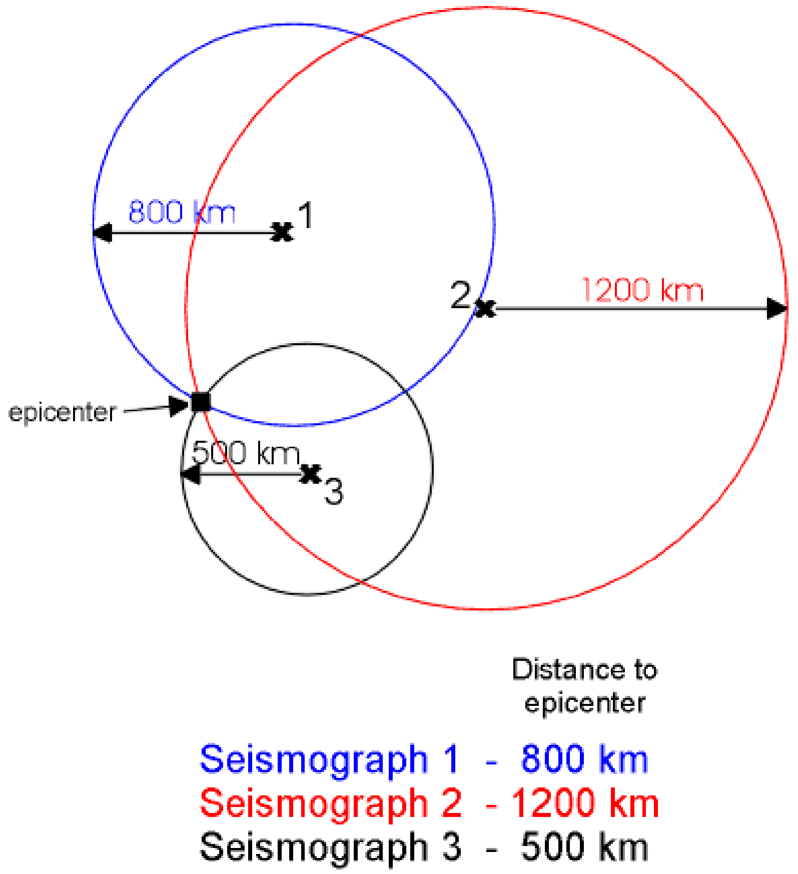
Recording Earthquakes

What happens:

1. P Wave arrives first, followed by S Wave. P Wave travel times about 2.5 times those of S Wave due to differing path of travel. Travel times vary systematically to a distance of 11,000 km from the focus.
2. Beyond 11,000 km P Waves are delayed several minutes over predicted arrival time and S Waves do not arrive at all. Why?

Locating Earthquakes

1. Difference between arrival times of P and S waves is determined. This gives distance to the epicenter from the seismograph.
2. Three seismographs are triangulated to give actual location of the epicenter (**Figure**).
3. Once distance to epicenter is known a correction factor is applied to amplitude of largest wave (usually S) to determine magnitude.



Distribution of Earthquakes

- Average about 150,00 quakes a year. About 6,000 are strong enough to be recorded.
- Generally most of the energy is released in the one or two large quakes which occur each year. Due to log scale, energy of all others barely total that of the large quakes.
- Occur in belts coincident with those of active volcanoes. These belts lie along plate boundaries and can be used to outline the plates.

Prediction and Control

A. Prediction
    1. Stress Meters
    2. Tilt Meters
    3. Recording Small Quakes
    4. Changes in Fluid Pressure in Wells
    5. Observing Animal Behavior

B. Control

1. Evidence indicates that fluid injection can trigger small movements along earthquake faults. But study is still in its infancy.

Structure of the Earth (See Figure from Introduction)

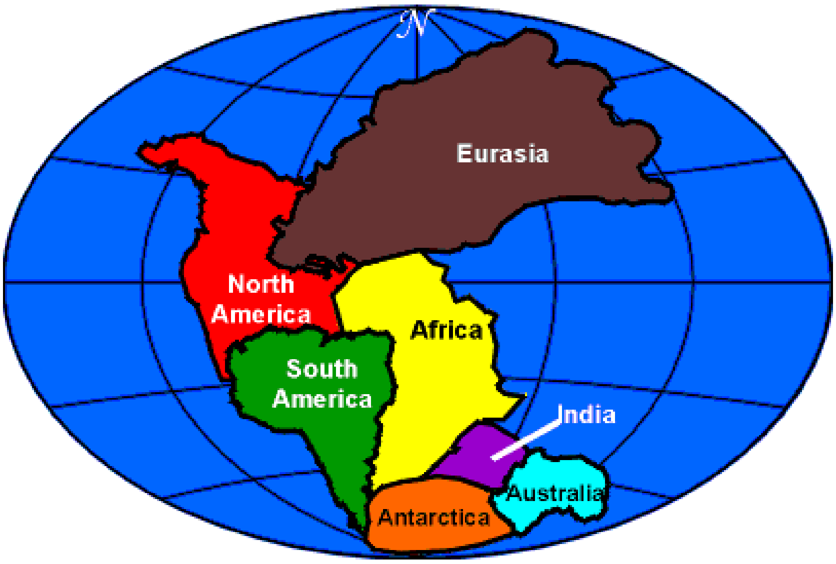
- Crust - Averages 33 km in thickness beneath the continents. Varies from about 20 km to 60 km. Seems to consist of an upper granitic layer, underlain by gabbro (?). onclusion based on increase in the velocity of P waves. Beneath oceans crust only 5 km thick and not layered. Consists entirely of basalt/gabbro.
- Mantle - Separated from crust by Mohorovichic Discontinuity (Moho). This is a zone of abrupt increase in P and S wave velocity. Indicates major change in the nature of the mantle. Mantle thought to consist largely of peridotite with lesser eclogite (metamorphic basalt) and dunite (olivine-rock). Mantle is a solid or near solid with a density of about 3.3 gr/cm^3. Extends to a depth of 2900 km.
- Core

    1. Outer core - 2,200 thick. Must be liquid due to disappearance of S waves and abrupt slowing of P waves. Probably consists of iron, nickel and some silicon.
    2. Inner Core - 1270 km thick. Probably a solid, but not known. Consists of same elements as outer core. Density of core about 15 gr/cm^3.

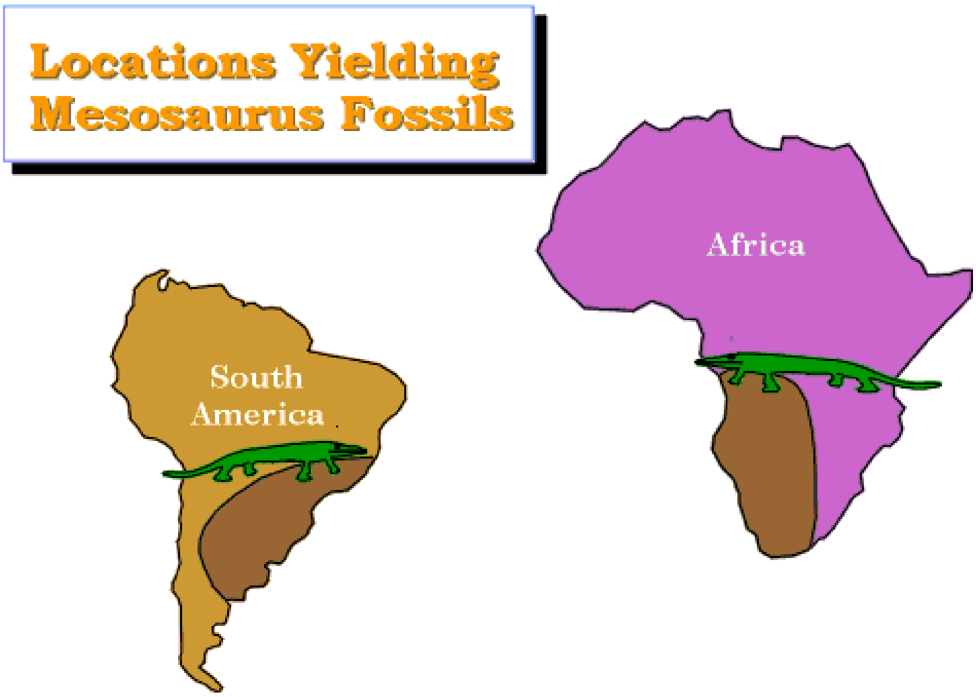
PLATE TECTONICS

Continental Drift

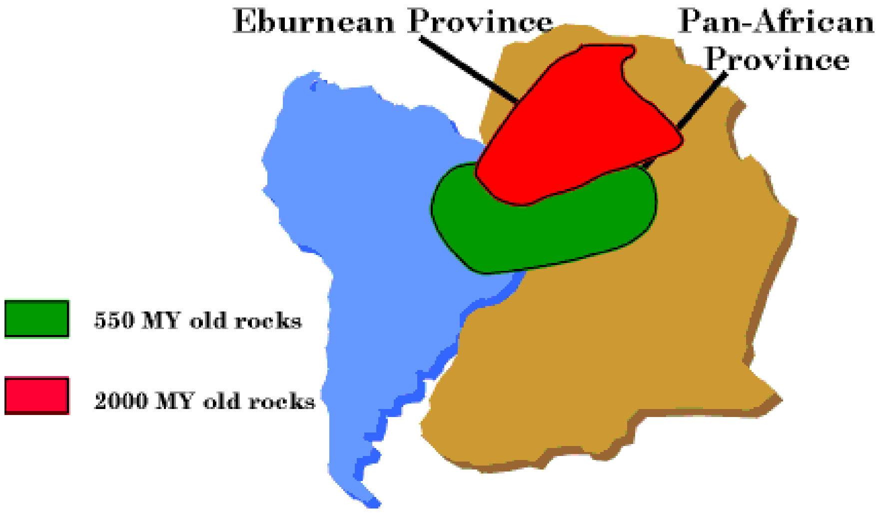
Alfred Wegener first proposes Continental Drift in his book published in 1915. Suggests that 200 million years ago there existed one large supercontinent which he called **Pangaea** (All Land)(**Figure**). This was not really a new idea, but Wegener offered several lines of evidence in support of his proposal.



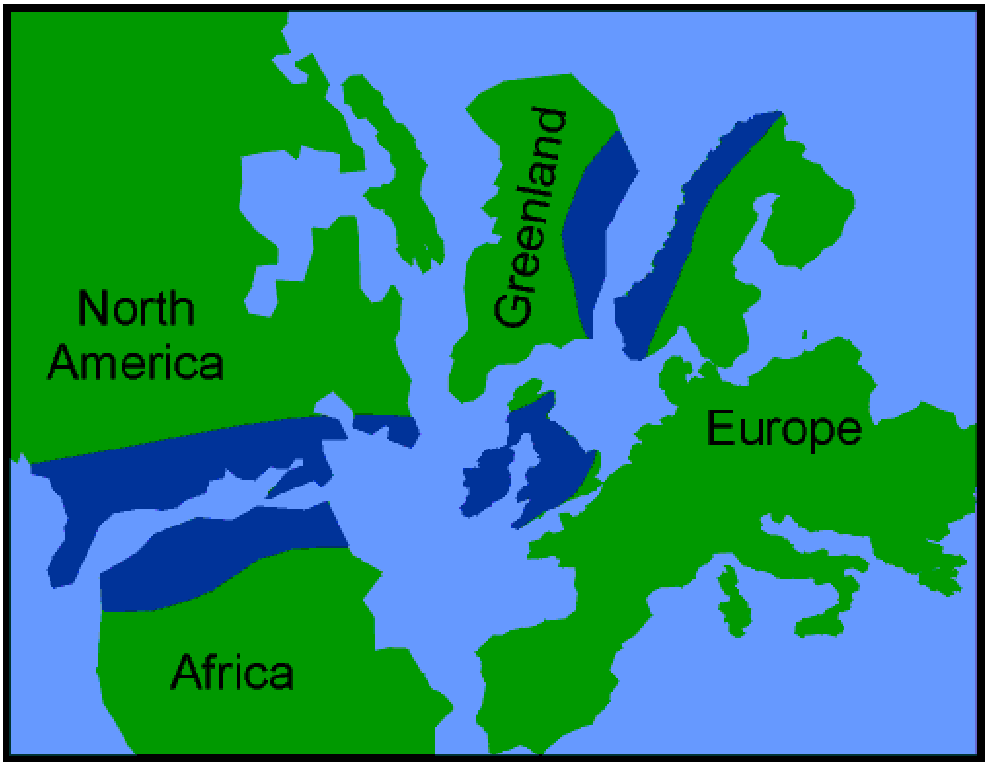
1. Fit of the Continents - Noted the similarity in the coastlines of North and South America and Europe and Africa. Today the fit is done at the continental shelf and it is nearly a perfect match.
2. Fossil Similarities - Mesosaurus, (**Figure**) reptile similar to modern alligator which lived in shallow waters of South America and Africa.



3. Rock Similarities
    a. Rocks of same age juxtaposed across ocean basins. **(Figure)**



    b. Termination of mountain chains. **(Figure)**



4. Paleoclimatic Evidence
    a. Glacial deposits at equator
    b. Coral reefs in Antarctica

Idea was rejected by North American geologists because Wegener couldn't come up with a mechanism for continental drift. Suggested tidal forces, but physicists showed this to be impossible. Wegener dies in 1930 and his idea dies with him.

Magnetism and Paleomagnetism

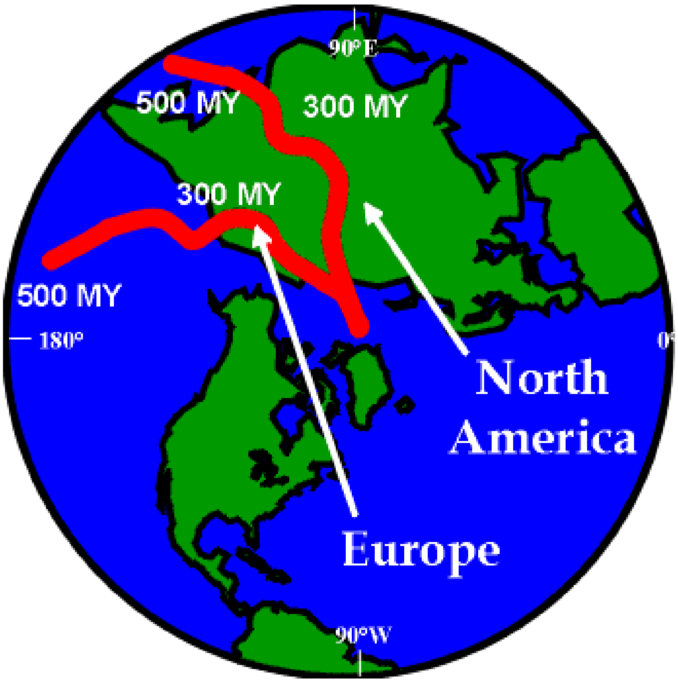
Earth is a bar magnet with a magnetic north and south. At poles a compass needle dips vertically. Downward at the north pole, upward at the south pole and horizontal at the equator. Magnetic poles do not correspond with geographic poles. Variation is termed the magnetic declination. It is 16 degrees east in California. However, it has been found that even though the magnetic and geographic poles do not correspond today when the location of the magnetic north pole is averaged over a 5,000 year period it does correspond with geographic north. Magnetic pole moves as much as 25 km per year.

Causes of Earth's Magnetism

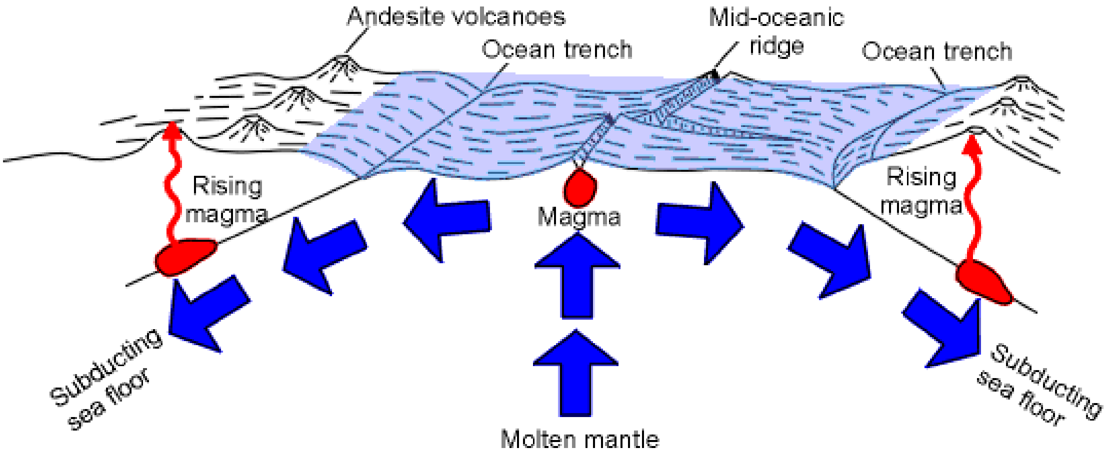
- First thought to be the result of a permanently magnetized core. However, it has been shown that when any substance is heated above 500 degrees C it looses its permanent magnetism.
- Earth is a Dynamo - Outer core is a fluid consisting largely of iron, so it is an excellent conductor. Electromagnetic currents are generated and amplified by motion within the liquid caused by convection. Rotation of the Earth unifies the random convective movements generating the magnetic field.

Paleomagnetism

In the 1950's scientists discover how to measure paleomagnetism (magnetism frozen in the rock at the time it formed). With this knowledge scientists could tell the direction and latitude of geomagnetic pole at the time the rock formed. Europeans were the first to extensively study paleomagnetic pole locations and found that by 500 MY ago magnetic north was located near Hawaii. At first it was assumed the poles were free to wander (**Apparent Polar Wandering**). North American geologists attempted similar studies largely to disprove the Europeans and found that 500 my ago North American rocks showed the magnetic north pole to be in the East Pacific, 3000 miles to the west of the European magnetic north at that time. (**Figure**)



At the same time a series of bathymetric surveys of the ocean basins revealed a system of ridges and trenches with high heat flow over the ridges. H. Hess (1962) rushes to print with the idea of Sea Floor Spreading. Postulates convection cells beneath ocean basins to drive the spreading.(**Figure**)



Fred Vines supports Hess with his explanation of symmetrical magnetic stripes on either side of the Atlantic Mid-ocean ridge (**Figure**).

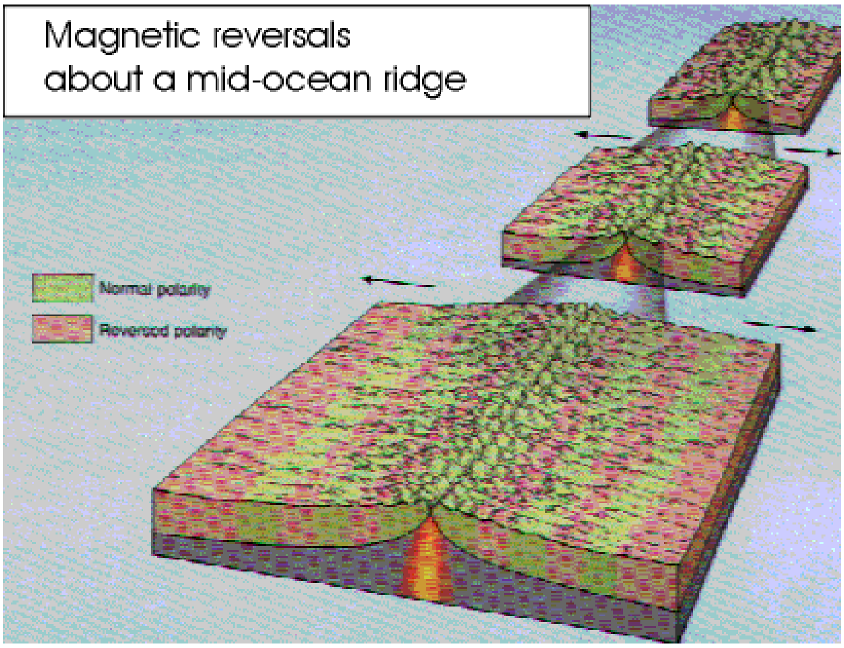


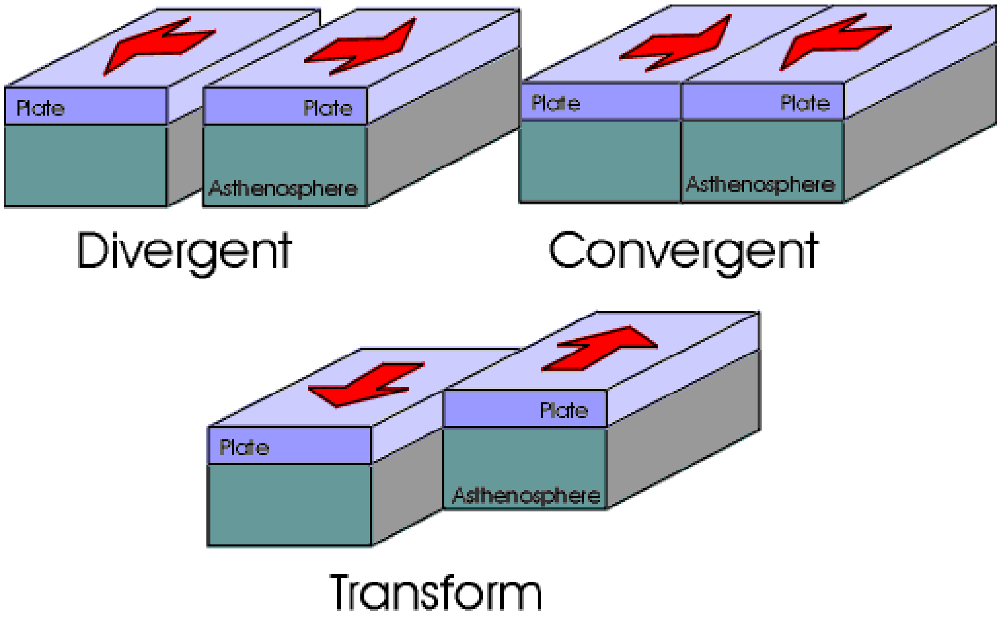
Plate Tectonics

Theory of Plate Tectonics is born. **Plate** - is a rigid piece of lithosphere floating on a partially plastic substrate (asthenosphere).

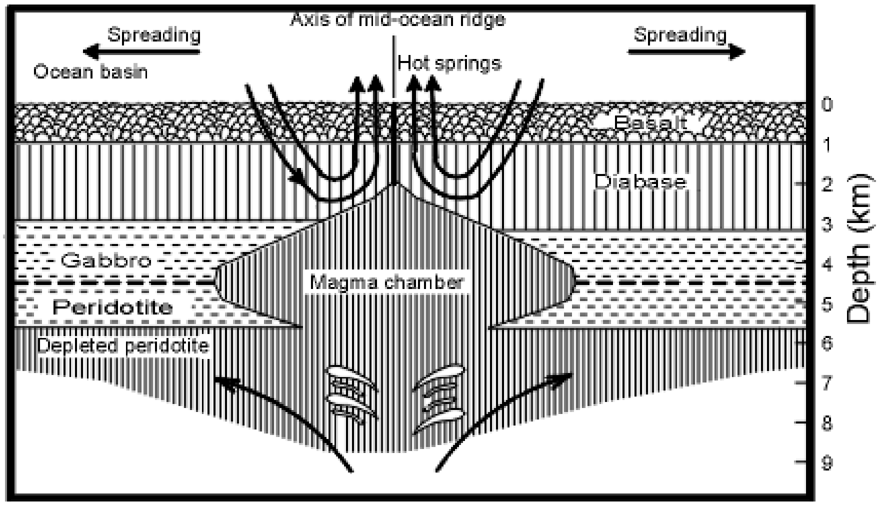
Seven Major Plates (**See Figure in your Text**)

1. Pacific
2. North American
3. South American
4. African
5. Eurasian
6. Antarctic
7. Indo-Australian

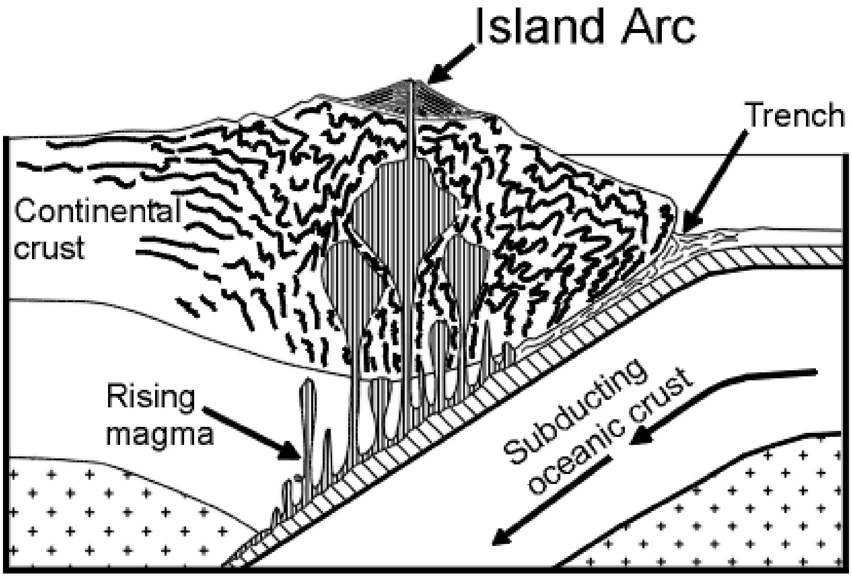
*Types of Plate Boundaries **(Figure)***



A. Divergent (**Figure**)- Spreading Center - Constructive Margin. Characterized by ocean ridges and sea floor spreading.

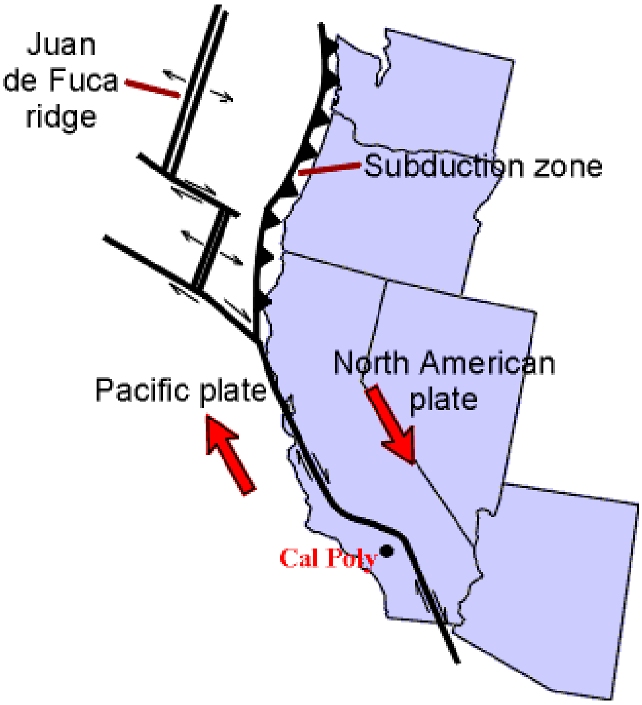


B. Convergent - (**Figure**) Characterized by trenches and island arcs



1. Ocean - Ocean (Japanese Islands)
2. Ocean - Continental (Cascade Mountains)
3. Continent - Continent (Himalayas)

C. Transform - Plates moving past one another along strike- slip faults. (**Figure**)

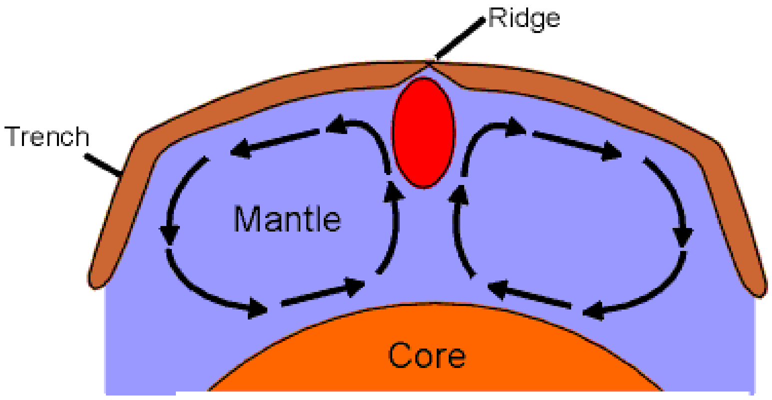


Additional Evidence in Support of Plate Tectonics

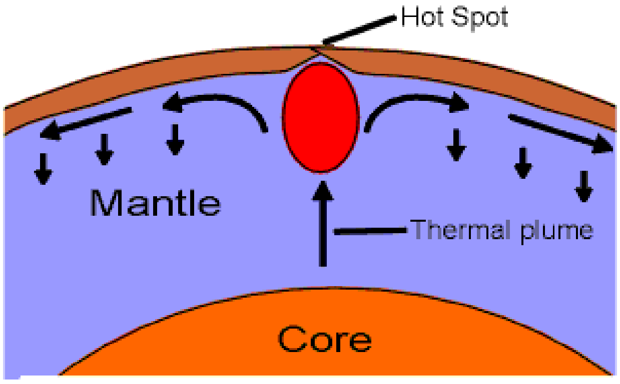
- Distribution of earthquakes along plate margins
- Location of earthquake foci along steeply-dipping subduction zones
- Age dating sediments on either side of the ridge indicates the sediments get progressively older away from the mid-ocean ridge axis
- Thickness of sediments also increases away from ridge

*Driving Force (**Figure**)*

1. Convection Cells
2. Hot Spots



Convection Model



Hot Spot Model

OCEANOGRAPHY

Branches of Oceanography

1. Physical Oceanography - study of the motions of seawater, particularly waves currents and tidal motion.
2. Chemical Oceanography - chemistry of seawater and reactions between the atmosphere and hydrosphere. More recently looks at how changes in seawater temperature (El Nino) and salinity affect global climate.
3. Biological Oceanography - study of life in the oceans, includes marine biology and ecology.
4. Geological Oceanography - study of the shape and geologic features of the ocean floor.

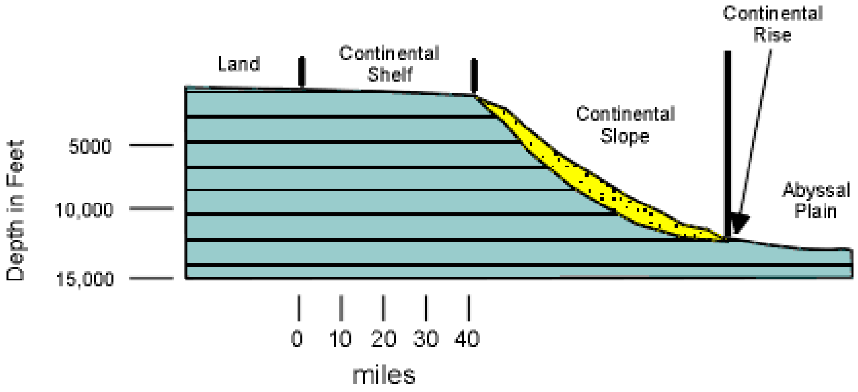
Geology of the Ocean Floor

The ocean basins are characterized by a series or recognizable geologic/topographic features (**Figure**). While the size of each feature varies within the various ocean basins they are always present:

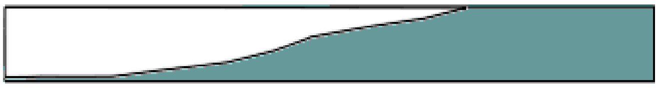
1. Continental shelf - the gently (<1−) sloping platform at the edge of the continent. The shelf is generally thought to be an extension of the continent and not really a part of the ocean basin. The average water depth on the shelf is about 75 meters, varying from zero at the shoreline to about 150 meters near its edge. A typical continental shelf is 60 kilometers wide, but it exceeds 100 kilometers off the Florida coast and is less than a few kilometers wide in places along the West Coast of South America. The rock underlying the thin veneer of sediments is granite similar to the basement rock elsewhere beneath the continents.
2. Continental slope - the continental slope marks the transition between the shelf and deep ocean floor. It has an average slope of 3-6−. This way not sound like much, but over a distance of 100 kilometers water depth increases from 75 meters to 4000 meters. Typically, continental slopes are crisscrossed by a series of deep submarine canyons the origin of which is controversial. Some represent drowned stream valleys, but others were clearly never above sea level and can not have been cut downward by stream erosion.
3. Continental rise - represents the accumulation of sediment at the base of the continental slope. Result is a gentler slope and the buildup of "turbidite" deposits. Uplifted turbidite deposits are common along the coastline of southern California, particularly at Blacks and Torrey Pines beaches north of San Diego. Southern California turbidites are thought to form during major earthquakes which cause sediments to slide off the edge of the shelf and

accumulate on the ocean floor as "fining upward" sequences of sedimentary rocks.

4. Abyssal plain - the ocean floor (covers about 30% of the earth's surface). The average water depth is around 5000 meters. Consists of a layer of unconsolidated sediment underlain by sedimentary rock and pillow basalt (**Figure**).



Continental Shelf and Slope off New York



Continental Shelf and Slope off San Francisco

Sea Floor Sediments

Sediments found on the floor of the ocean (abyssal plain) fall into three distinct categories. The percentages of each vary from place to place within the ocean basin and appear to be a function of deep ocean currents, prevailing wind patterns and local volcanism.

- Lithogenous sediment - derived from the weathering of continental rocks and volcanic eruptions.
- Biogenous sediment - comprised of the remains of organisms. When the sediment contains 30% or more organic material it is termed ooze. Oozes are further subdivided into calcareous oozes, which are only found in water depths less than 3000 meters, and siliceous ooze that occur throughout the deeper portions of the ocean basin.
- Hydrogenous sediment - precipitated directly from seawater. Most common type of hydrogenous sediment is a manganese nodule. How and why they form remains something of a mystery, but probably requires a

contribution from hydrothermal waters generated by heat from subsea volcanoes.

Composition of Seawater

Ion	wt %
Chlorine	1.92
Sodium	1.07
Sulfate	0.25
Magnesium	0.13
Calcium	0.04
Potassium	0.04
Others	0.02
TOTAL	3.47

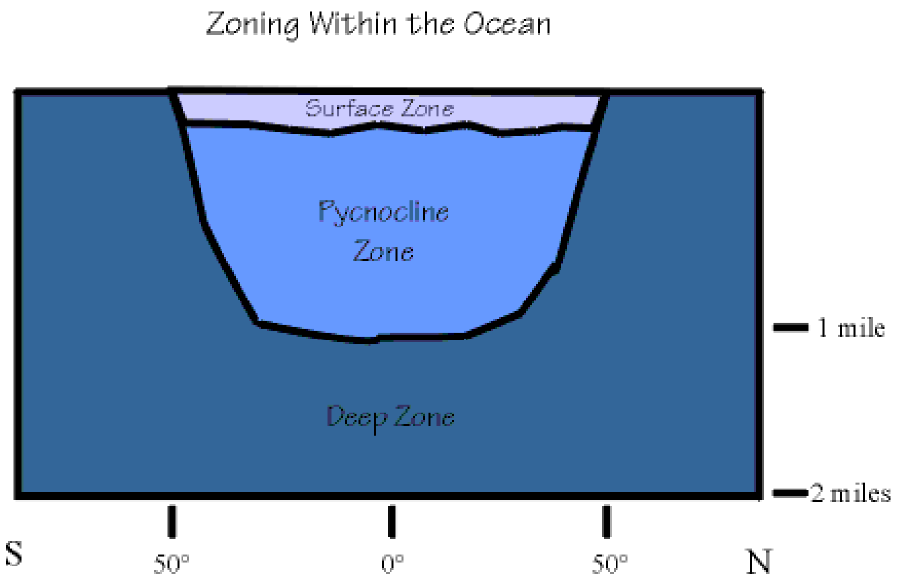
The average salinity of seawater is 3.47% but oceanographers choose to report salinities in parts per thousand (*ppt*). Since wt% is the same as parts per hundred, all we need to do is multiply by 10. This gives a value of 34.7 ppt for average salinity. Ocean water is very homogeneous but locally the salinity can vary from 33 ppt near the Poles to 41 ppt in arid, enclosed basins such as the Red Sea.

Scientists recognize the ocean is actually comprised of a series of layers (**Figure**). These layers represent differences in water temperature and salinity. The layering is a function of geographic latitude and water depth. The three layers are:

- Surface Zone - warmest water. Does not extend beyond 50^{-} north or south of the equator. Is only about 2% of the ocean's volume. In this zone the water is thoroughly mixed due to thermal energy from the Sun. This zone does not extend below the depth to which appreciable sunlight penetrates seawater (a few hundred meters).
- Transition Zone (pycnocline) - density changes rapidly with depth. Since density of seawater is a measure of salinity and temperature we are looking at the zone in which the effect both are changing. This zone is also

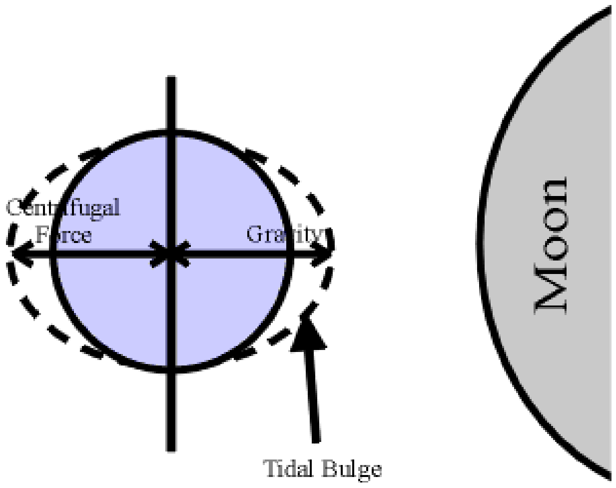
absent near the poles. About 18% of all seawater. Extends to a depth of 1800 meters.

- Deep Zone - 80% of all seawater. Temperature and salinity are very uniform and show little or no local variation.

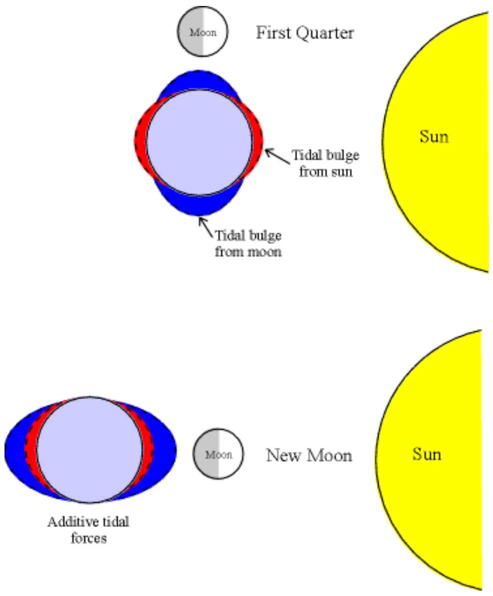


Tides

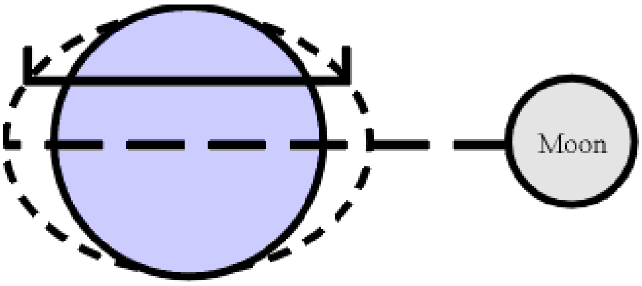
Tides are caused by the gravitational attraction of the moon and the sun (**Figure**). Although the mass of the moon is much less than that of the sun it is also much closer and hence its tidal pull is about twice that of the sun. A tidal day lasts 24 hours and 53 minutes, the time for the moon to make one complete revolution about the earth. However, the complete tidal cycle takes 19 years because of two complications:



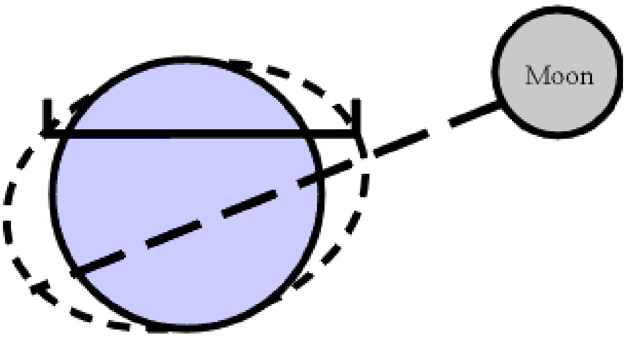
- the moon and earth have elliptical orbits so their distance from one another and the sun varies. Since tidal forces are due to the pull of gravity and the force of gravity is inversely proportional to distance the height of tides will be a function of distance to the sun and moon. Further, tidal forces can be additive when the sun and moon are aligned relative to earth producing very high (Spring) tides (**Figure**).



- the tilt of earth's axis also effects the position of the sun and moon with respect to the equator. This causes local variation in tidal height as a function of latitude and season (**Figure**).



Moon over the Equator



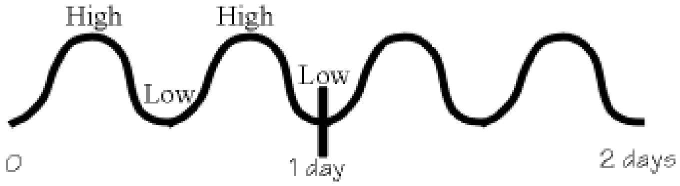
Moon above the Equator

*Types of Tides (**Figure**)*

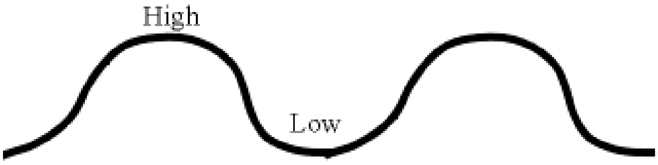
1. Semidiurnal - two high and two low tides of the same height in 24 hours.
2. Diurnal - one high and one low tide in a 24 hour period. Common along Gulf Coast of U.S.
3. Mixed - two high tides and two low tides of differing heights during a 24 hour period (California)

Not well understood what causes the different types of tides, but probably a function of the geometry of the coastline. Open coastlines such as West Coast experience mixed tides, while partially enclosed basins like the Caribbean experience diurnal tides with highs and lows varying by less than a meter

Semidiurnal Tides



Diurnal Tides



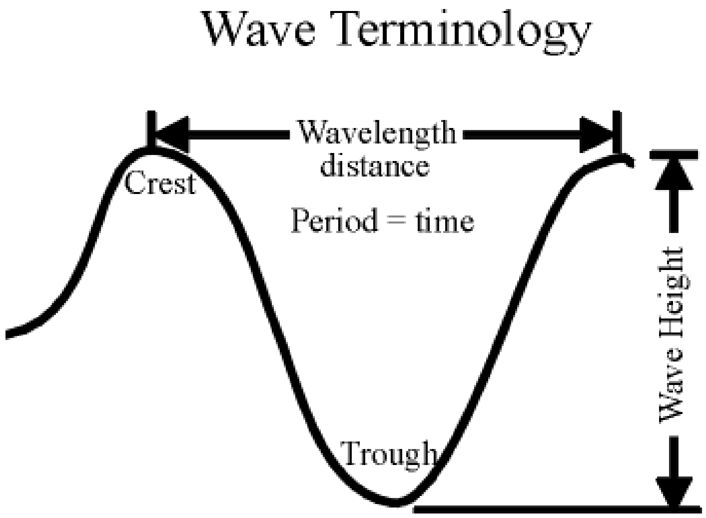
Mixed Tides

OCEANOGRAPHY II

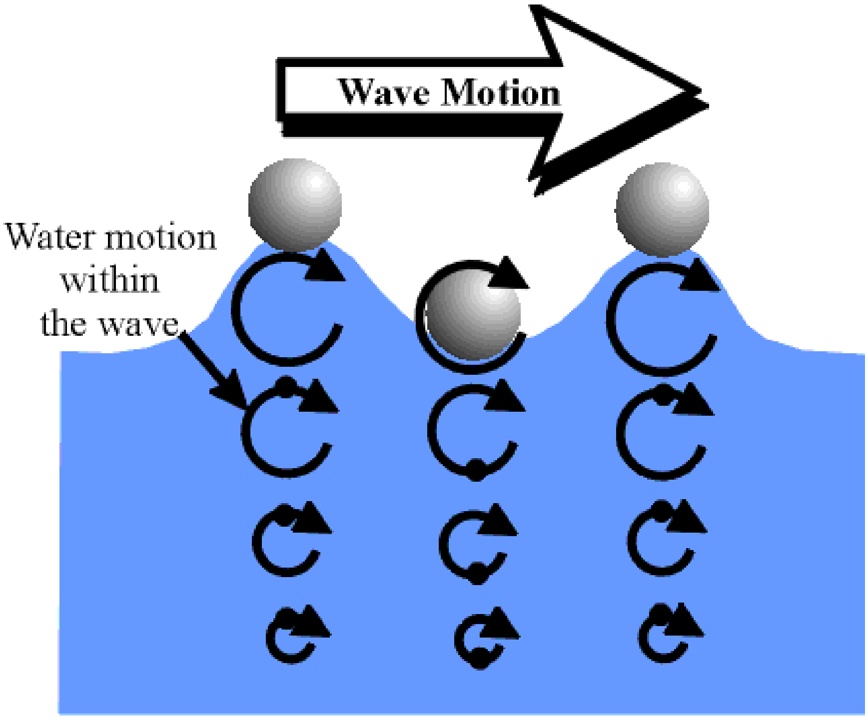
Waves

Characteristics (**Figure**)

- Height (H)
- Period (T) - time between successive crests
- Wavelength (L) - distance between successive crests

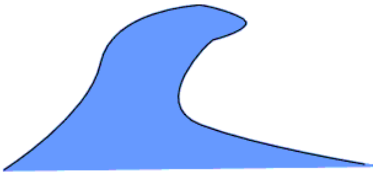


Velocity in Deep water = 1.56T (m/sec) and wavelength = $1.56T^2$ (m). In deep water only the wave form moves (**Figure**) while in shallow water both the wave form and the water moves. In shallow water the waves will touch bottom when the water depth = ス L. Friction slows the wave causing H to increase and L to decrease. Also, front of wave is slowed more than rear, thus it breaks. Waves break when H = 1/7 L or about a depth = 1ス H. Since waves rarely exceed 6 meters in height, this limits wave erosion to depths of less than 10 meters. There are two types of breaking waves: (**Figure**)

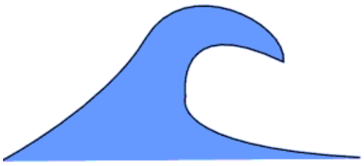


Negligible turbulence below 1/2 wavelength

- Spilling waves - typical breaking wave.
- Plunging waves - top of the wave curls over trapping an air pocket. Trapped air generates foam when the wave breaks. (Storm-generated waves)



Spilling Wave



Plunging Wave

Swells - large, long period waves formed by the recombination of two or more waves during storms. Can travel thousands of miles. Not unusual for swells that hit California beaches to be generated near Australia.

Average wave height = 2 meters; 10-15% exceed 15 meters; largest ever witnessed 35 meters in height.

Waves are caused by **wind**. Wave height is dependent on:

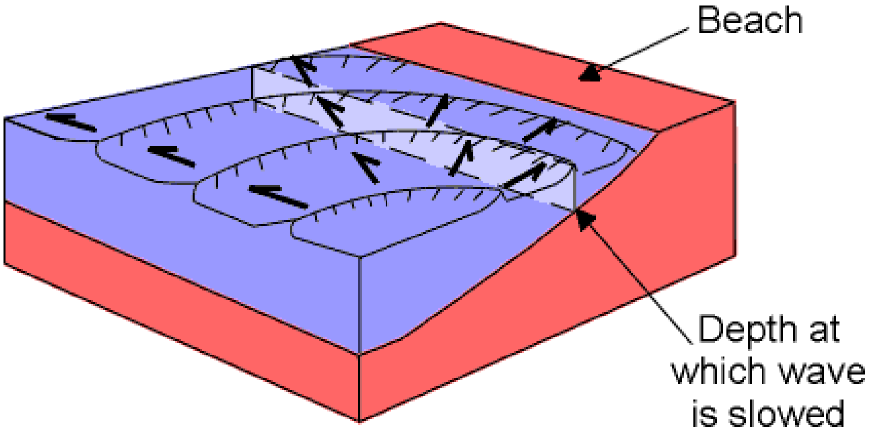
- wind velocity
- how ling the wind blows over a given area
- fetch - the distance over which the wind blows

The shoreline is often divided into distinct zones by the nature of the wave erosional forces present:

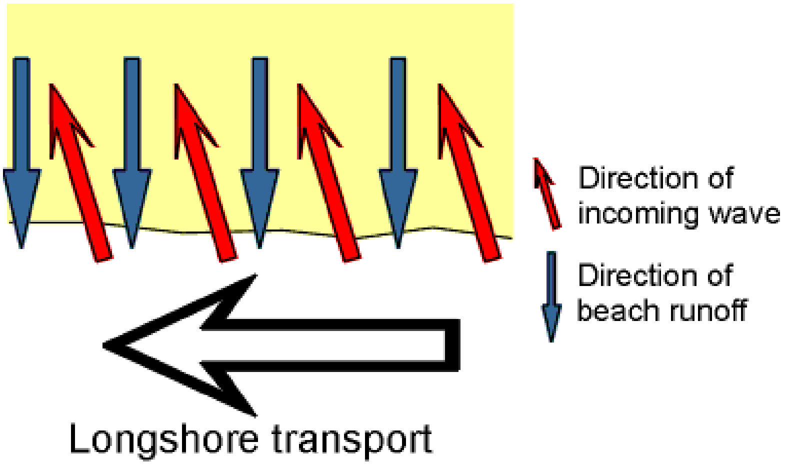
1. Offshore - that portion of the shoreline beyond the breaker zone where water depths exceed 6 meters.
2. Inshore - includes the breaker zone and surf zone. In the former, waves crest and break. The surf zone is characterized by foam and turbulence from the breaking waves.
3. Foreshore - the swash zone where breaking waves surge up onto the beach. Top of the swash zone is marked by a berm or ridge of sand created by wave erosion and surge.
4. Backshore - that portion of the beach not effected by present day wave activity.

Refraction and Longshore Currents

Refraction - change in a waves direction as it approaches a coastline. Due to drag on waves approaching a coast obliquely. Effect is to cause waves to approach nearly parallel to the shore (**Figure**).



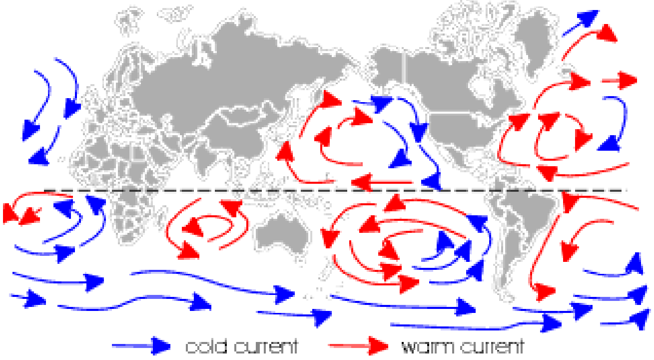
Although refraction bends the waves until they are nearly parallel to the coast, they nonetheless still approach at a slight angle. This results in a *longshore current*. The current is caused by the slight oblique angle of the wave, but runoff that is perpendicular to the slope of the beach. This causes grains of sand to be moved along the shore (**Figure**).

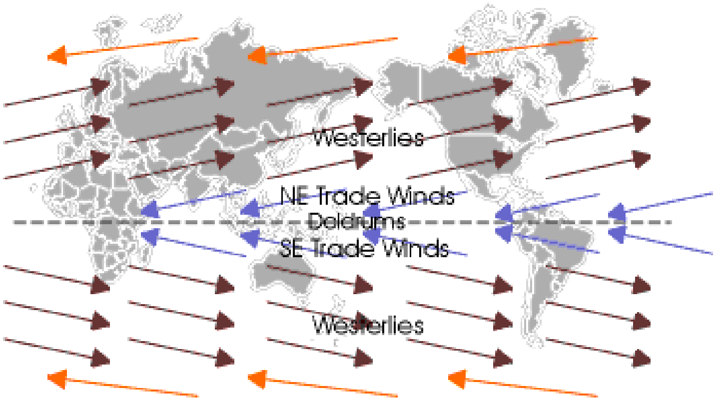


Currents

Currents are driven by the wind. The general effect of currents is to move warm water toward the poles and cold water toward the equator. A major factor in the movement of ocean water is the Coriolis effect. Can use the analogy of a slow moving artillery shell. The shell travels a straight path but the Earth rotates beneath it (Coriolis effect) causing theshell to be deflected relative to the observer. The same process effects currents.

Gyres - Closed loops formed by currents. Major gyres are centered about 30−N and S of the equator. Continents have a major effect. At 60− S, where no continents are present currents circle the Earth. (**Figure**)



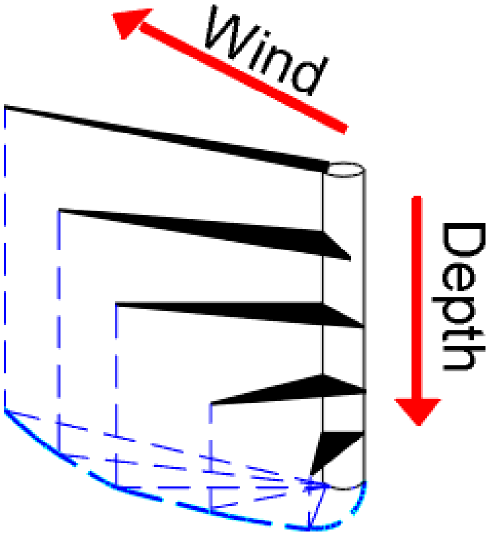


Typical major gyre consists of:

- Two equatorial currents moving westward on either side of the equator. These are driven by the Trade Winds.
- In between is a weak eastward-moving Equatorial Countercurrent. The weak current is due to the absence of wind currents at the equator (Doldrums). Equatorial currents move at about 2-4 miles per day which allows for maximum heating.
- When the warm currents near the continents they are deflected north and south by the continents and the Coriolis effect. (Example: Gulf Stream along the east coast of the U.S.) Currents move rapidly (25-75 miles per day) and remain warm.
- At about 40− N and S the Prevailing Westerly winds deflect the currents to the east. Water cools as it moves eastward.
- Reaching the continents the current is again deflected by the continent and Coriolis effect, completing the gyre.

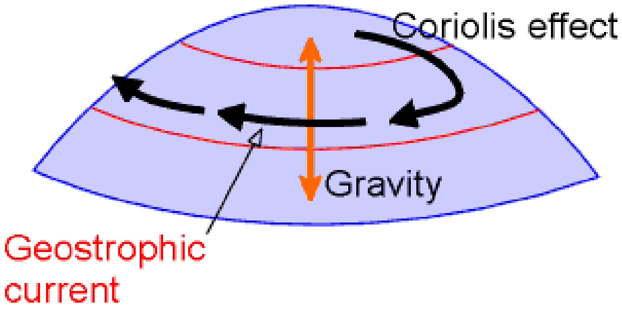
Geostrophic Currents

Wind movement and the Coriolis effect combine to cause currents to move at 45 − to the actual wind direction. The surface layer drags the next layer of seawater below it which is deflected even farther than the surface layer. This continues downward with depth all the way to the ocean bottom. This is called the Eckman Spiral (**Figure**).



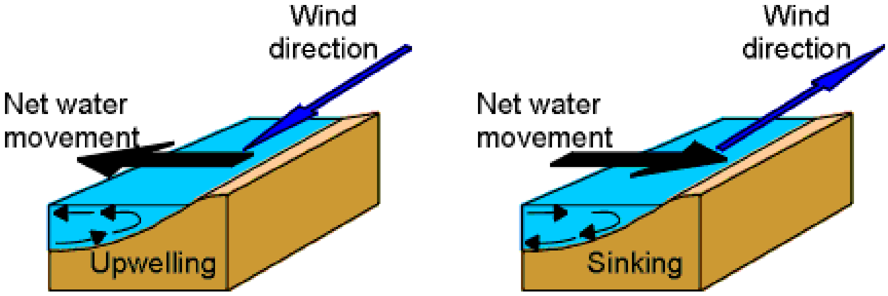
However, at an average wind speed of 30 mph at a depth of 300 feet the water is moving slowly in the opposite direction from that at the surface. This is considered to be the bottom limit of wind driven currents. The net result of this entire process is actually to cause the water to move at a right angle to the wind direction or toward the center of a gyre. This causes hills up to 6 feet high in the center of a gyre.

The mounded water flows downward and outward from the "hill" under the influence of gravity, but the Coriolis effect deflects it to the right continuously until it is flowing parallel to the hill at which point gravity and the Coriolis effect are balanced. This is termed a geostrophic current (**Figure**).



Vertical Currents

Because prevailing winds along most coastlines blow more or less parallel to the shoreline (reason to be discussed later in the course) they push the water either toward the shore or offshore causing sinking currents or upwelling currents (**Figure**). The later are especially important to commercial fishing since upwelling currents provide nutrients for marine life.



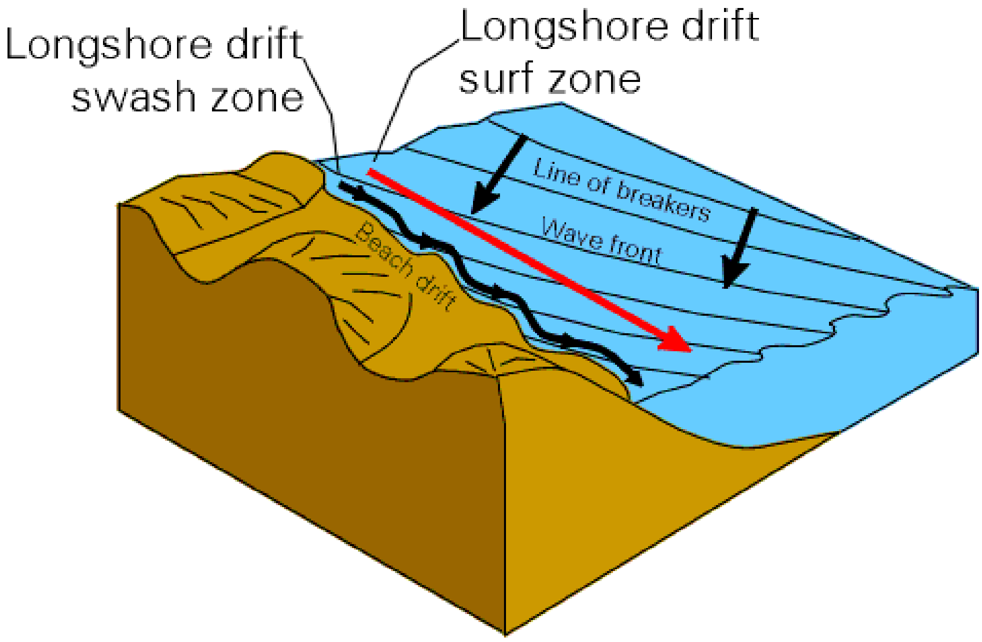
Deep Ocean Currents

As noted previously the ocean is layered with differences in salinity and temperature. Since dense, cold water sinks and warm water rises there is a net effect of cold Polar water sinking and moving both northward and southward toward the equator. The cold current flowing along the ocean floor displaces the warmer water upward.

Longshore Current

As waves approach a coastline they undergo a change in direction. They touch bottom and the dragr causes the waves to approach nearly parallel to the shore (refraction).

Although refraction bends the waves until they are nearly parallel to the coast, they nonetheless still approach at a slight angle. This results in a *longshore current*. The current is caused by the slight oblique angle of the wave, but runoff that is perpendicular to the slope of the beach. This causes grains of sand to be moved along the shore (**Figure**).



Coastal Features (slides)

Passive Coastline (East coast)

- barrier island - sand bar formed offshore along gently sloping beaches with little wave erosion (Outer Banks)
- spit - hook-shaped sand bar extending from a headland (Cape Cod)
- tombolo - a sand bar extending from an island to the coast
- lagoon - area of quiet water and high organic activity behind a barrier island
- eustuary - area of brackish water caused by water of seawater and river water

Active Coastline (West coast)

- sea cliff - flat bench uplifted by tectonic activity to form a cliff
- wave cut bench - erosional feature found near shoreline of an active coast
- beach terrace - somewhere between a wave cut bench and sea cliff
- stack - headland cut by wave erosion
- sea arch and sea cave - early stages in the formation of a stack

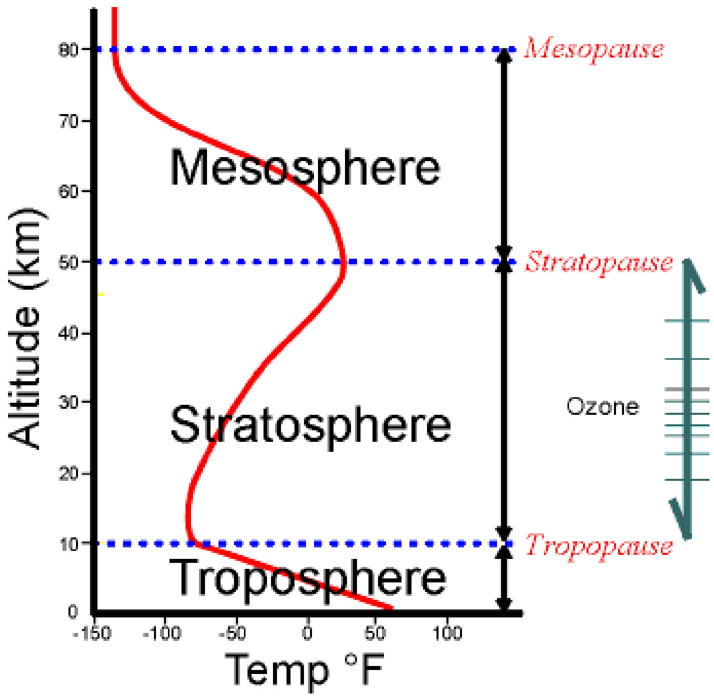
MOISTURE, CLOUDS and PRECIPITATION

Meteorology - study of the atmosphere

- Weather - study of short-term changes in the atmosphere.
- Climate - the combination of weather elements that characterize an area over a long term. Takes into account seasonal changes as well as short term extreme fluctuations.

Composition of the Atmosphere	
Gas	Volume %
Nitrogen	78
Oxygen	21
Argon	1
All others	<1
Locally	up to 3% water vapor

Structure of the Atmosphere **(Figure)**



- **Troposphere** - lowest layer of the atmosphere where weather occurs. Temperature falls 3.5−F per 1000 feet. Top lies at about 6-7 miles. Temperature varies from an average of 60− at the surface to -60− at the top of the troposphere. **Tropopause** - top of the troposhere.
- **Stratosphere** - top of the tropopause to about 30 miles. Temperature is constant to about 20 miles then increases to the stratopause. At the stratopause the temperature is about 40−F. The temperature rise is due to the presence of an ozone layer. The ozone absorbs incoming UV radiation increasing the heat content of the gas. At about 18 miles the ozone reaches its maximum concentration, about 5ppm. Without the ozone layer the Earth's surface would be warmer and the UV level much higher.
- **Mesosphere** - extends from 30 miles to about 50 miles. Temperature falls to -120−F at the mesopause.
- **Thermosphere** - extends above the mesosphere more than 100 miles. Zone of increasing temperature, but this is meaningless since there is in effect no atmosphere present.

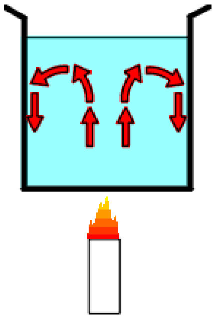
Heat

Heat is a form of energy. **Temperature** is a measure of the quantity of heat energy. Actually each is a function of molecular motion, the faster a molecule is vibrating/moving the greater the heat energy and the higher the temperature.

Temperature is measured with a **thermometer**. The most common, the alcohol thermometer, measures the differential expansion of red alcohol and the glass that encloses it.

All weather is a function of heat transfer. There are three forms of heat transfer.

1. Conduction - heat travels through material by molecular collisions. The analogy is a hot spoon.
2. Convection - heat transfer by actual motion. For example (**Figure**) heated water is less dense so it rises and the colder water at the surface sinks to take its place



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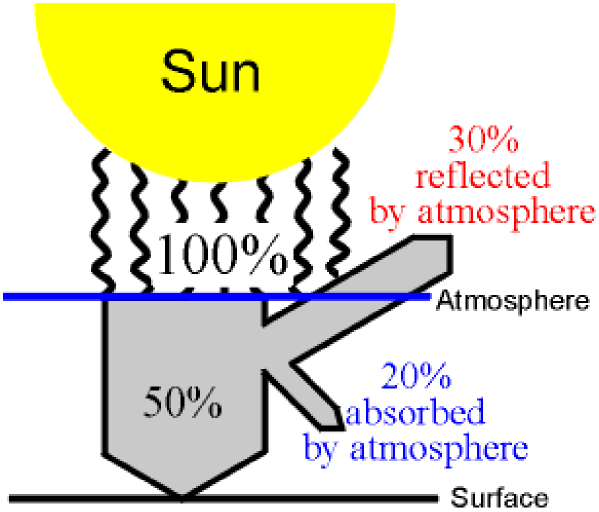
3. Radiation - transfer of energy by electromagnetic waves. The radiant heat of the sun passes through the vacuum of space and is absorbed by the Earth.

Heat Balance

Sun emits energy in the wavelength from 0.5 µ m to 10 µ m. This includes some ultraviolet and infrared energy as well as visible light.

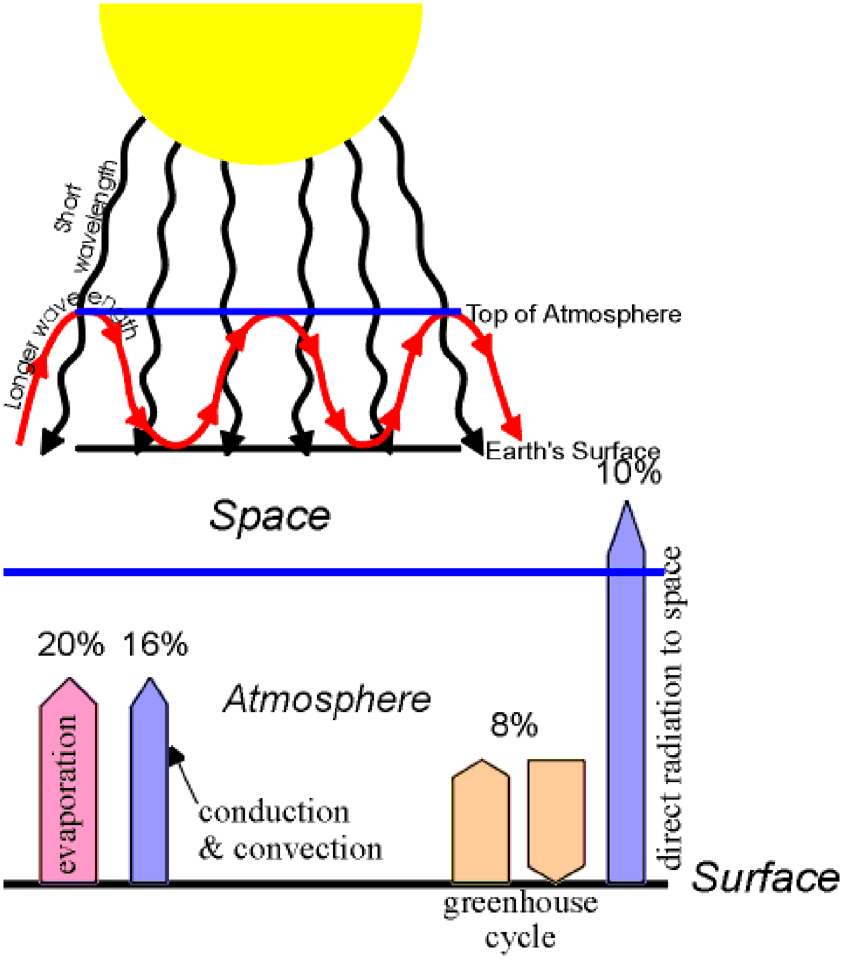
Ozone and oxygen absorb most of the ultraviolet. Water vapor and carbon dioxide absorb infrared.

70% of the Sun's radiant energy penetrates the Earth's atmosphere (**Figure**). 30% is reflected by the atmosphere- albedo.



Greenhouse Cycle

Greenhouse Effect - (**Figure**) Earth like the Sun radiates energy, but since it is a smaller body it radiates in the infrared. Carbon dioxide in the atmosphere absorbs significant quantities (**Figure**) of this energy and reradiates it to Earth. It is estimated that the temperature on Earth is 63-F warmer than it would be if there were no greenhouse cycle.



Sun's Illumination

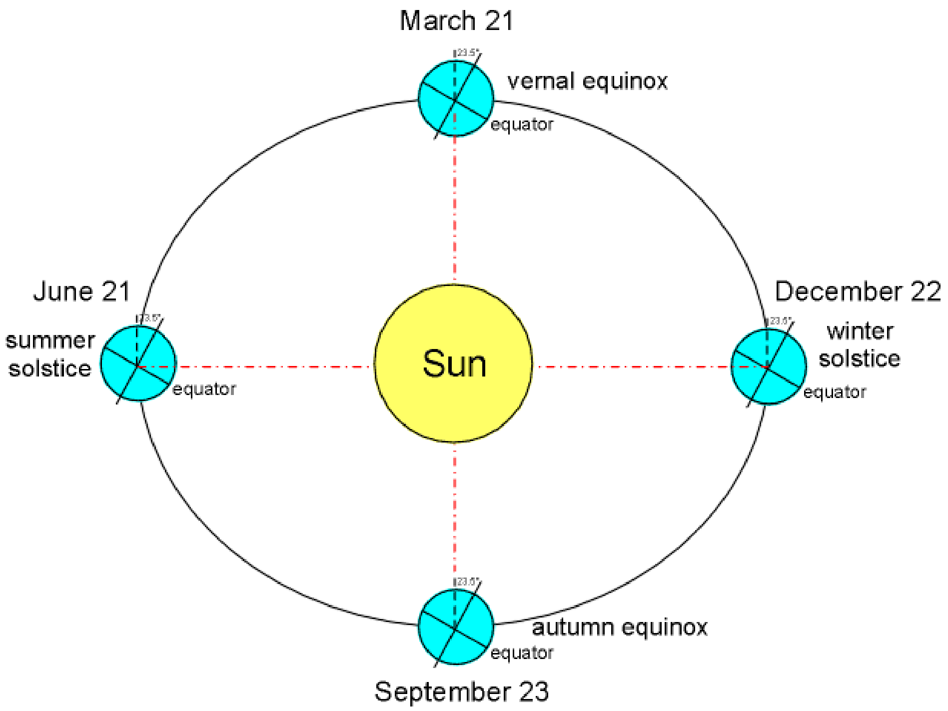
Effected by the inclination of the Earth's axis, which in turn causes the seasons. Earth's geographic poles are tilted 23.5− from the vertical. This dramatically influences the amount of radiant energy striking various points on the Earth's surface.

The days when the axis is tilted *exactly* 23.5− toward the Sun are termed the solstices:

- June 21 - summer solstice
- December 22 - winter solstice

Equinox - days when the Earth's axis is at right angle to a line between the center of the Earth and Sun.

- March 21 - vernal equinox
- September 23 - autumn equinox (**Figure**)



Tropic of Cancer and Capricorn - point on the Earth's surface where rays from the Sun strike the Earth at a perpendicular angle at noon on the solstice. Located 23.5− north or south of the equator.

Arctic Circle - boundary marking the part of the Earth which remains in daylight or darkness for 24 hours during the solstice. Located 66.5− north or south of the equator.

Obviously, the tropics receive more thermal energy than the poles. Weather and seasons result from the tendency of the Earth to disperse this uneven heat distribution.

Moisture in the Atmosphere

Humidity - measure of the amount of water vapor in the atmosphere:

- Absolute humidity - the mass of water vapor in a given volume of air (g/m^3).
- Relative humidity - the amount of water vapor in air relative to the maximum it can hold at a given temperature. Expressed as a percentage. Relative humidity is temperature dependent, the higher the temperature the air, the more moisture it can hold.

Dew Point - point at which the relative humidity = 100%. At the dew point theoretically *condensation* will occur. In reality, unless dust or other particulate matter is present the air must be supercooled to produce condensation.

Dew - condensation in the form of water vapor.

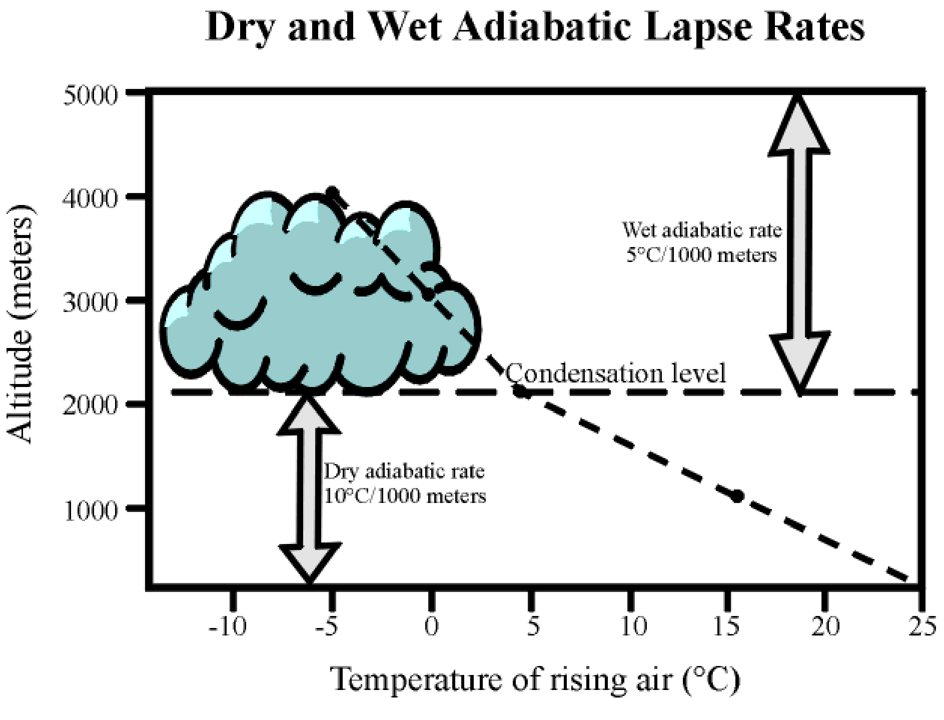
Frost - condensation as a solid, below the freezing point.

Clouds form when warm moist air rises (**Figure**). The process of *adiabatic cooling* accompanies this. As the air cools, it looses its capacity to hold moisture and condensation in the form of clouds appears.

Dry adiabatic lapse rate = 10−C per 1000 meters

Wet adiabatic lapse rate = 5−C per 1000 meters

Normal lapse rate = 6−C per 1000 meters



Clouds (See slides in class)

Clouds are classified by 1) shape and 2) elevation.

Elevation

1. Low - ground level - 6500 feet

2. Medium - 6500-23,000 feet
3. High - 23,000 feet +
4. Clouds of vertical development (span two or more elevation zones)

Shape

1. Stratus - layered
2. Cumulus - look like cotton balls, generally have flat bottoms and rounded tops
3. Cirrus - thin, wispy

Low Clouds

1. Fog - cloud layer very close to the ground
2. Nimbostratus - low layered cloud
3. Stratocumulus - low level cumulus cloud often seen during the clearing stages of a storm

Medium Clouds

1. Altostratus - mid level layered clouds
2. Altocumulus - mid level cumulus clouds

High Clouds

1. Cirrostratus - high, thin layers, often invisible to the eye from the ground
2. Cirrocumulus - high cotton ball-like clouds
3. Cirrus - typical high level thin, wispy clouds

Vertical Clouds

1. Cumulonimbus - thunderheads with tremendous vertical extent (25,000 meters)

Precipitation

Not nearly as straightforward as it may seem. The average cloud droplet is 0.01 - 0.02 millimeters in diameter. At that size, it would take 48 hours to reach the surface of the Earth if it began to fall. It would evaporate before it reached the surface. How then does precipitation occur? This remains largely a matter of speculation. Clearly, the droplets must grow in size, but how? Two theories:

1. Coalescence - some droplets are able to fall to earth under the influence of gravity. These collide with others and grow. This is probably the least important process.

2. Supercooling - at the top of a cloud ice forms because the temperature is below freezing. If supercooling occurs the process literally sucks all the available moisture from around the ice crystal forming a much larger ice crystal, which then melts as it falls to earth.

Types of Precipitation

- Rain - droplets >.5 mm in diameter
- Drizzle - droplets .1 - .5 mm in diameter
- Snow - aggregates of ice crystals several mm in diameter
- Sleet - rain or drizzle which freezes before reaching the ground
- Freezing rain - rain which freezes upon reaching the ground

PRESSURE and WIND

Acts in all directions because the atmosphere is a gas. Example: the weight of air on the roof of a typical house is about 2,000,000 pounds, however the roof does not collapse because the same force acts on both the top and bottom of the roof.

In the atmosphere as air is heated it expands. Because it expands it becomes less dense and therefore, rises. This creates an area of low pressure at the surface. As the warm air rises it begins to cool, eventually causing it to sink back to the surface creating an area of high pressure. In general, air flows towards areas of low pressure and away from areas of high pressure.

Measurement of Pressure

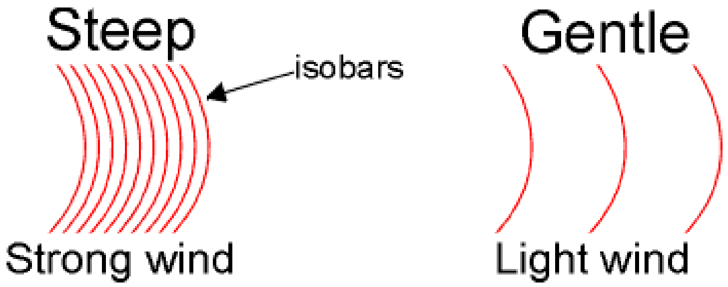
1. Mercury barometer - the pressure air exerts on a column of mercury. At sea level this pressure averages 29.92 inches.
2. Aneroid barometer - uses a partial vacuum that expands or contracts as a function of changing atmospheric pressure. Same device as an altimeter in airplanes.

Pressure is usually given in inches of mercury by television weathermen. But the National Weather Service reports pressure in millibars. For those scientists out there one millibar = 10 newtons.

Wind

Caused by pressure gradients. Wind is an attempt to equalize the pressure differential. This differential is the result of unequal heating of different portions of the Earth's surface.

Pressure Gradient - the change in air pressure with distance.**(Figure)**



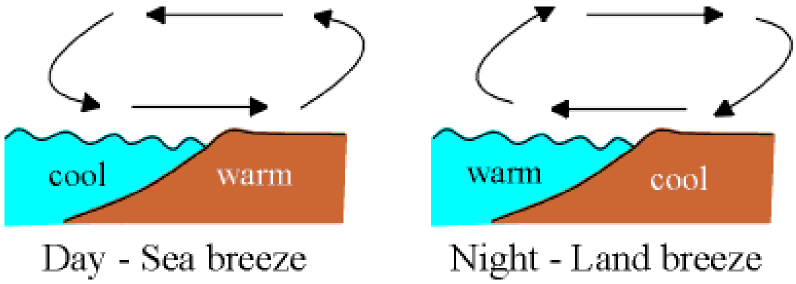
Winds start blowing perpendicular to the pressure gradient, but the Coriolis effect deflects the wind to the right in the Northern Hemisphere. Results in a spiral-like effect in which the winds end up blowing parallel to the pressure isobars.

Wind direction is generally given as the direction from which the wind is blowing. Therefore a westerly wind would be one that blows from west to east.

Types of Winds

- Cyclone - low pressure system, wind blows in a counterclockwise direction
- Anticyclone - high pressure system, clockwise wind circulation

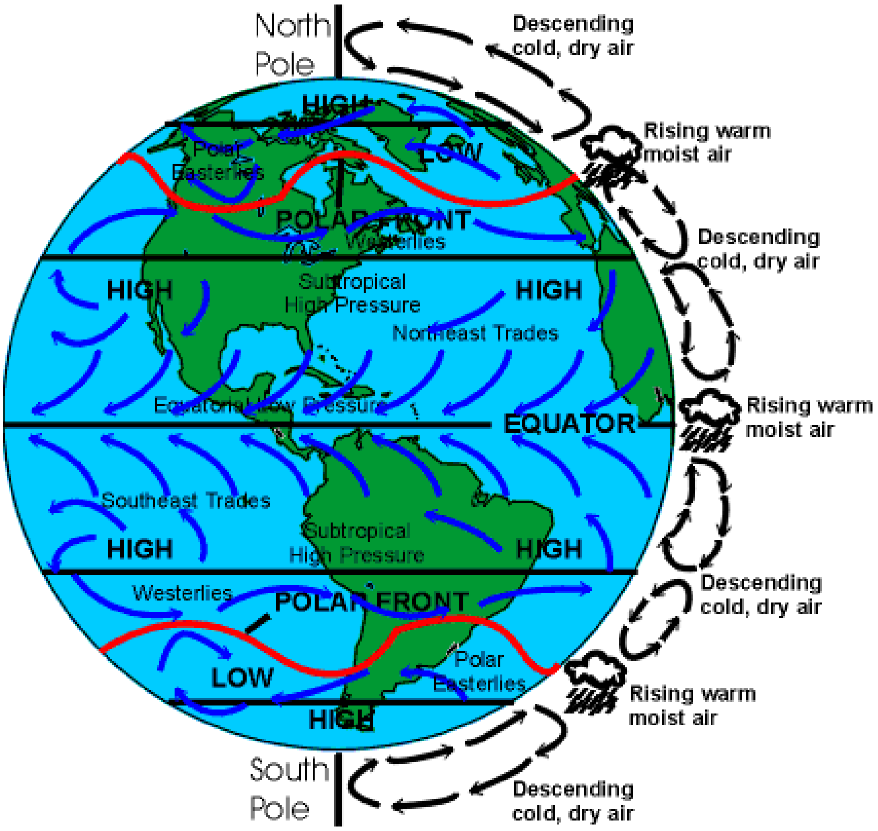
- Land-Sea Breeze - **(Figure)** result from differences in temperatures of the land surface and ocean. During the daytime the land heats up more rapidly than the ocean, the warm air rises and cool air blows in from the ocean to take its place. At night the opposite occurs. The land cools quickly while the ocean remains warmer. The wind direction reverses itself and blows offshore as the warm ocean air rises and the cooler air from the land moves in to take the place of the rising air.



- Monsoons - seasonal land-sea breezes. During the winter cool, dry air flows offshore to the ocean. In the summer cooler, moist air from the ocean flows landward. If it is pushed upward by a mountain range it looses its moisture as it rises and cools.

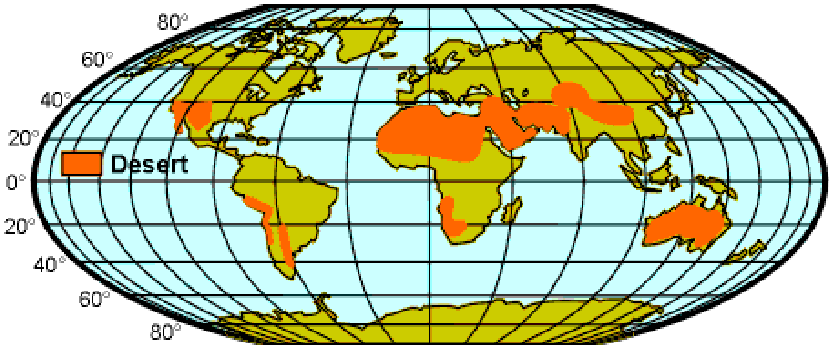
- Chinook Winds - warm, dry winds that flow downslope. Occurs when a low pressure system is on the lee side of a mountain range. Air rushes downslope toward the low and is heated by compression. Example, Southern California Santa Ana Winds are caused when air moves down through passes from the high desert to the coastline. It is heated by compression due to the pressure increase at sea level relative to the typical 3000 foot altitude of the high desert.

Global Wind Circulation (Figure)



1. At the equator the Earth receives the maximum amount of thermal energy from the Sun. This causes equatorial air to rise, losing its precipitation in the process.
2. Steady surface winds are absent in this area (doldrums), but aloft the winds diverge to flow northward or southward toward the poles. As the wind flows to the north or south the Coriolis effect deflects it. At about 30 degrees N or S the winds are flowing due east.
3. As the air moves northward it cools. By 30 degrees north latitude it is cool enough it begins to sink to the surface creating the subtropical high pressure areas. It warms as it cools and since it lost most of its moisture at the equator it is very dry (note that most desert are located 30 degrees N

or S of the equator)**(Figure)**. Since the air movement is vertical there is an absence of surface wind in the "horse latitudes".



4. The descending air splits with some flowing back toward the equator and some continuing poleward. Surface winds blowing toward the equator are deflected until they are blowing from the northeast (in the Northern Hemisphere) to give us the "Trade Winds".
5. The winds flowing toward the poles are also deflected by the Coriolis effect to give us the prevailing "Westerlies" of the middle latitudes.
6. At the poles the cold air sinks and flows toward the lower latitudes. It is deflected to give the polar "Easterlies". These converge with the prevailing Westerlies at the Polar Front at 60 degrees N or S of the equator.

This global circulation model is termed the **three-cell model**. Keep in mind, this is only a general model and local geography as well as seasonal changes have considerable effect on patterns of wind circulation.

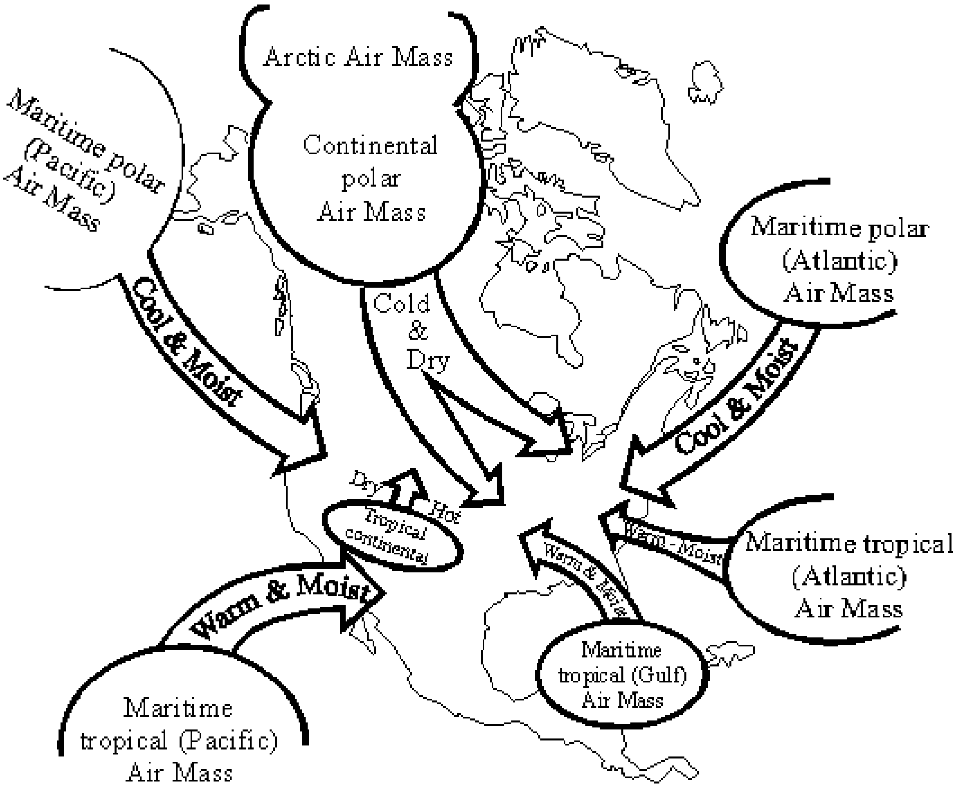
Air Masses

Large volumes of air that have uniform characteristics at any given latitude. Air masses are named for where the originate:

- Arctic/Antarctic (A) - at the poles
- Polar (P) - to the south (or north) of the polar front
- Tropical (T) - form in the region from 30 to 60 degrees north or south of the equator
- Equatorial (E) - form near the equator

Sub-classified as:

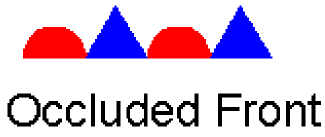
- Continental (c) - form over continents (dry)
- Maritime (m) - form over oceans (moist)


Arctic Air Mass
Maritime polar (Pacific) Air Mass
Continental polar Air Mass
Maritime polar (Atlantic) Air Mass
Cool & Moist
Cold & Dry
Cool & Moist
Dry
Hot
Tropical continental
Warm - Moist
Maritime tropical (Atlantic) Air Mass
Warm & Moist
Warm & Moist
Maritime tropical (Gulf) Air Mass
Maritime tropical (Pacific) Air Mass

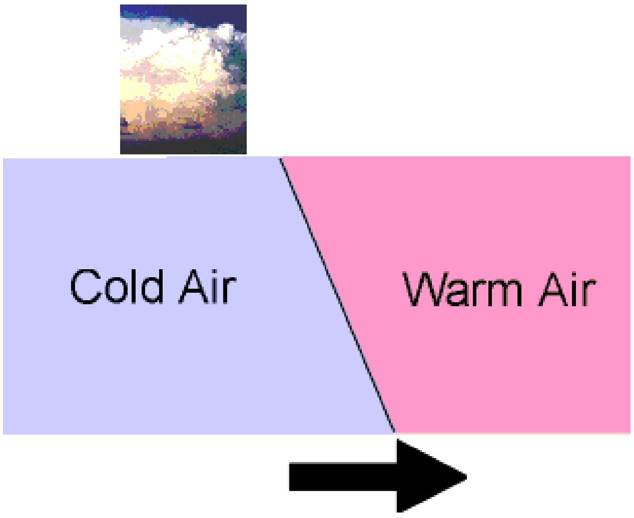
FRONTS and STORMS

Front - Boundary separating two air masses of different type.

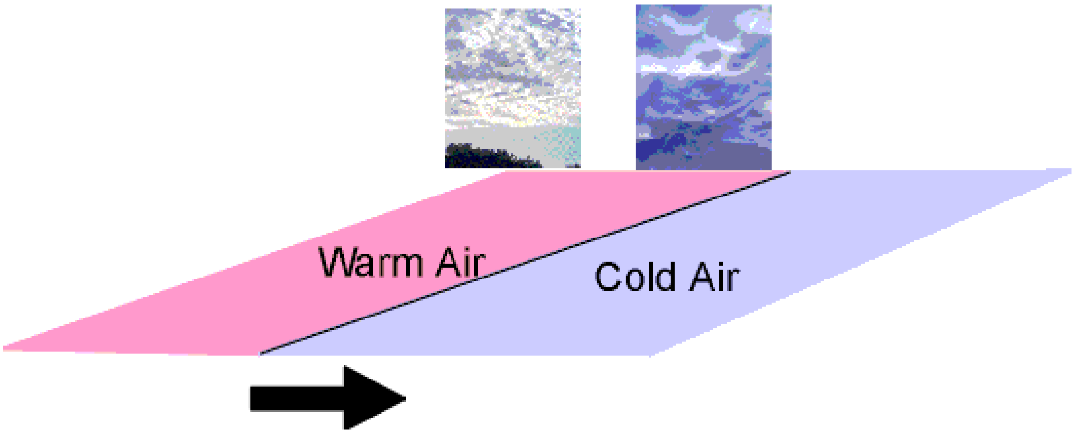
Types of Fronts



a. Cold Front - cold air moves into an area occupied by warm air. Steep frontal boundary with warm air forced up and over. Often accompanied by cumulonimbus clouds and thunderstorms. Move at speeds of 20-30 mph, followed by rapid clearing.



b. Warm Front - warm air moves into area occupied by cold air. Gentle slope to the front. Move at 10-20 mph. Cloud sequence cirrus, status, nimbostratus. Steady gentle rains.



c. Occluded Front - rapidly moving cold air overtakes warm air. Often associated with periods of prolonged heavy showers.
d. Stationary Front - boundary between warm and cold fronts that does not move appreciably.

Cyclonic Storms

In the northern hemisphere these are low pressure systems with counterclockwise air circulation that generally form at the polar front. At the front, cold polar air is moving eastward while warm, moist Pacific air is flowing to the west. Friction along the front causes waves as warm air overrides cold. A cyclone begins to develop. Eventually the cyclones spin off the polar front and are driven southeastward by the let stream. A typical "wave cyclone" has a life span of 7 to 10 days. As long as the frictional waves persist along the polar front a series of cyclones will be spawned.

Severe Storms

Thunderstorms - most serious form of severe weather because they kill more people each year than tornadoes or hurricanes.

- Local - associated with warm moist air masses. Commonly form during the afternoon or early evening.
    1. start when warm, moist air is forced upward
    2. condensation occurs and clouds form (cumulus stage)
    3. cloud grows upward until the top is below freezing and precipitation develops
    4. as precipitation falls, downdrafts are created pulling cold air downward (mature stage)
    5. cold air is replaced by warm air until the warm air supply is used up and the rainfall stops (dissipating stage)

- Organized thunderstorms - form along fronts. Longer and more persistent than local thunderstorms. They often form along squall lines associated with the passage of cold fronts.

Lightening - a complex process

1. Cloud droplet freezes from the outside inward. This concentrates + charges on the outside and - charges on the inside
2. Core freezes last and volume increase shatters the droplet
3. Heavy core falls toward the base of the cloud taking the - charges with it
4. Lighter external particles rise with + charge
5. Negative charge on the base of the cloud causes a positive charge to develop on the ground
6. Lightening flash begins when negative particles move down from cloud (Invisible Lightening Leader)
7. Return strokes (visible) result in reverse flow of + charges to the cloud. Can also move cloud to cloud.

Thunder - caused by the high temperatures generated by the lightening stroke which expands the surrounding air explosively.

Tornadoes - violent wind storms produced by a spiraling column of air that extends downward from a cumulonimbus cloud. Typical wind speeds average 300mph and can reach 500mph. Also there is a severe pressure drop in the center of the funnel. This combination of high wind speed and a near vacuum can be very destructive. The U.S. averages about 800 tornadoes a year, most from April through June. The Midwest is especially vulnerable in the spring because of the clash between cold polar air and warm Gulf air.

Formation of tornadoes is poorly understood. For some reason especially violent thunderstorms cause the air which rushes inward and upward to spiral downward creating a funnel from a few hundred feet to over a mile in width. The tornado travels along the ground, usually in a northeasterly direction, for distances of a few hundred feet to tens of miles eventually dissipating.

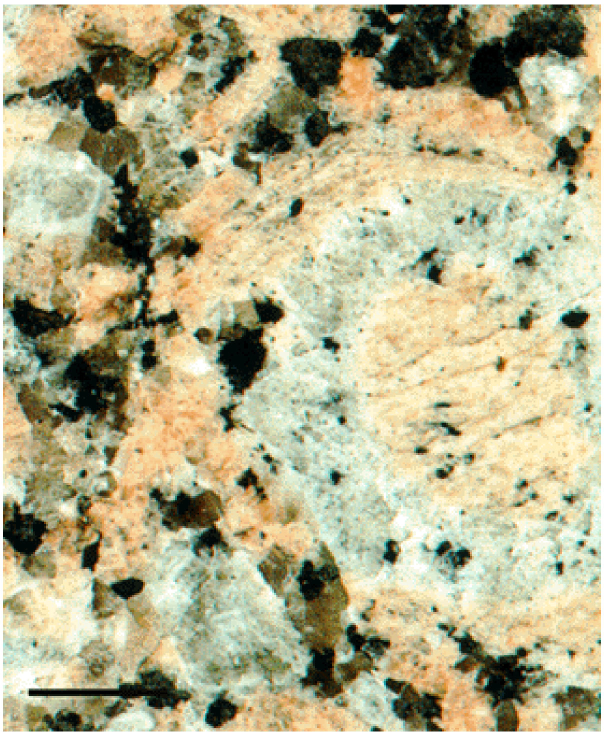
Hurricanes - tropical storms that move independent of a recognizable frontal boundary. Have wind speeds in excess of 75mph; the upper limit is about 200mph. Friction with the ground is the limiting factor.

Hurricanes form initially by surface convergence. The warm air spirals upward. As it rises, the latent heat of condensation heats the air further causing it to rise faster and higher. This sucks more toward the center of the hurricane. Eventually an eye forms which marks the upper limit of wind velocity. Inside the eye the winds are calm. Typically, a hurricane eye is 10 to 20 miles in diameter.

Hurricanes are spawned over the ocean in latitudes just to the north and south of the equator. They feed from the warm, moist water requiring a surface T of +80 degrees F, and can not be sustained over land or cold water. Areas of the U.S. that are especially susceptible to hurricanes are the Gulf Coast and southern Atlantic Coast. Hurricane season starts in June and runs through September.

Igneous Rock Identification

The eruption of a volcano is an awesome process. Unfortunately, (or fortunately!) most of us will never experience it in our lifetime. But we might have the opportunity to see the products of volcanic processes while driving across country or hiking in the woods. Volcanic rocks, the solidified products of volcanic eruptions are part of a larger group of rocks called igneous rocks.



IGNEOUS ROCKS

Igneous rocks are crystalline or glassy rocks formed by the cooling and solidification of molten magma. Igneous rocks comprise one of the three principal classes of rocks, the others being metamorphic and sedimentary.

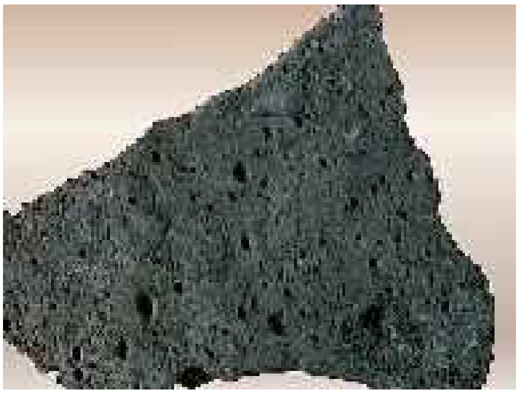
Igneous rocks are formed from the solidification of magma, which is a hot (600 deg.C - 1300 deg.C, or 1100 deg. - 2400 deg. F) molten or partially molten rock material. The Earth is composed predominantly of a large mass of igneous rock with a very thin covering of sedimentary rock. Whereas sedimentary rocks are produced by processes operating mainly at the Earth's surface such as weathering and erosion, igneous--and metamorphic--rocks are formed by internal processes that cannot be directly observed.

Magma is thought to be generated within the asthenosphere (the layer of partially molten rock underlying the Earth's crust) at a depth below about 60-100 kilometers (40-60 miles). Because magma is less dense than the surrounding solid rocks, it rises toward the surface. It may settle within the crust or erupt at the surface from a volcano as a lava flow. Rocks formed from the cooling and solidification of magma deep within the crust are distinct from those erupted at the surface mainly owing to the differences in conditions in the two environments. Within the Earth crust the temperatures and pressures are much higher than at its surface; consequently, the hot magma cools slowly and crystallizes completely. The slow cooling promotes the growth of minerals large enough to be identified visually without the aid of a microscope (called phaneritic, from the Greek phaneros, meaning "visible"). On the other hand, magma erupted at the surface is chilled so quickly that the individual minerals have little or no chance to grow. As a result, the rock is either composed of minerals that can be seen only with the aid of a microscope (called aphanitic, from the Greek aphanes, meaning "invisible") or contains no minerals at all (in the latter case, the rock is composed of glass, which is really a viscous, non-crystalline liquid). This results in two groups of igneous rocks: (1) plutonic or intrusive igneous rocks that solidified deep within the earth and (2) volcanic, or extrusive, igneous rocks formed at the Earth's surface.

The deep-seated plutonic rocks can be exposed at the surface for study only after a long period of weathering or by some tectonic forces that push the crust upward or by a combination of the two. The exposed intrusive rocks are found in a variety of sizes, from small dikes to massive dome-shaped batholiths, which cover hundreds of square miles and make up the cores of many mountain ranges.

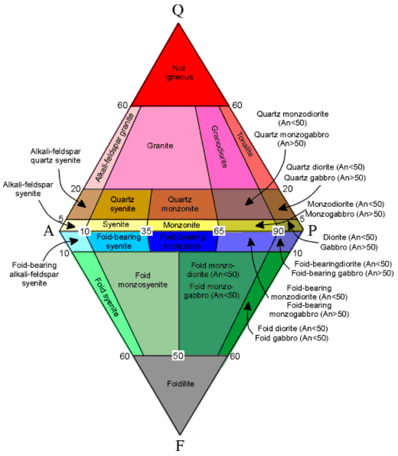
Extrusive rocks occur in two forms: (1) as lava flows that flood the land surface much like a river and (2) as fragmented pieces of magma of various sizes (pyroclastic materials), which often are blown through the atmosphere and blanket the Earth's surface upon settling. The coarser pyroclastic materials accumulate around the erupting volcano, but the finest pyroclasts can be found as thin layers located hundreds of miles from the opening. Most lava flows do not travel far from the volcano, but some low-viscosity flows that erupted from long fissures have accumulated in thick sequences. Both intrusive and extrusive magmas have played a vital role in the spreading of the ocean basin, in the formation of the oceanic crust, and in the formation of the continental margins. Igneous processes have been active since the formation of the Earth some 4.6 billion years ago.

CLASSIFICATION



Igneous rocks are classified on the basis of mineralogy, and texture. As discussed earlier, texture is used to subdivide igneous rocks into two major groups: (1) the plutonic rocks, with mineral grain sizes that are visible to the naked eye, and (2) the volcanic types, which are usually too fine-grained or glassy for their mineral composition to be observed without the use of a microscope. Being rather coarsely grained, phaneritic rocks readily lend themselves to a classification based on mineralogy since their individual mineral components can be discerned, but the volcanic rocks are more difficult to classify because either their mineral composition is not visible or the rock has not fully crystallized owing to fast cooling.

A plutonic rock may be classified mineralogically based on the actual proportion of the various minerals of which it is composed. In any classification scheme, boundaries between classes are set arbitrarily; however, if the boundaries can be placed closest to natural divisions or gaps between classes, they will seem less random and subjective, and the standards will facilitate universal understanding. The most commonly used scheme was devised by the International Union of Geological Sciences (IUGS)(See image).



While such a classification is desirable for petrologists, the average earth scientist relies on a much simpler scheme. That classification takes advantage of simple associations that occur among the various silicate minerals. We do not need to know percentages of the various mineral phases, merely which minerals are present. While not as accurate or precise as the IUGS classification if is more than adequate for field and lab studies. We will be utilizing this classification as our basis for identifying igneous rocks.

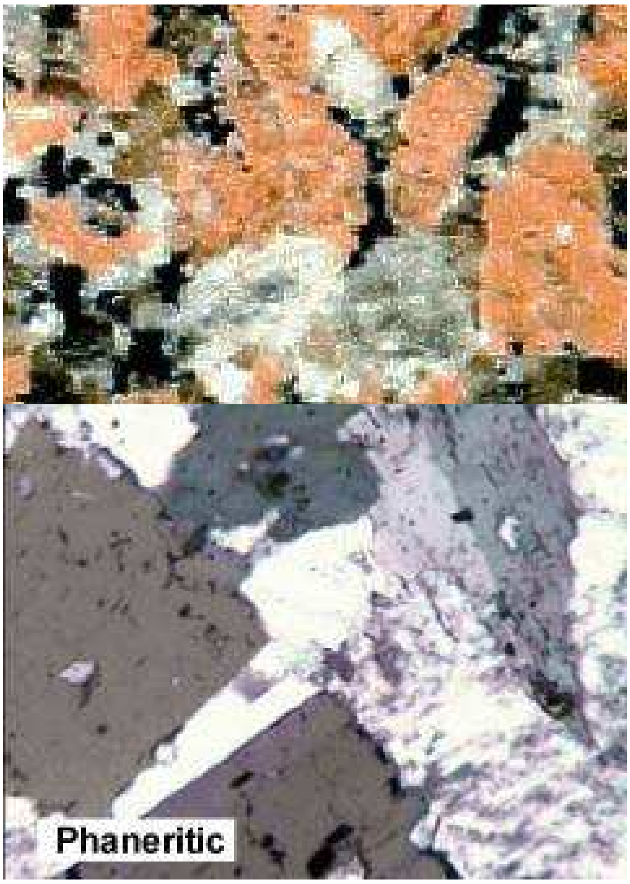
Volcanic rocks present a greater challenge. Since many of the mineral grains are not visible, using a mineralogical classification becomes problematic. Ideally we would like to have a chemical analysis. However, most lay people have little access to analytic facilities and a classification based on chemistry, although desirable, is rather impractical. Thus, most field classifications of volcanic rocks rely on the few phenocrysts we can see or the rock's color. The latter can be especially unreliable, but often it is the only clue me have. We shall attempt to rely on texture, color and phenocryts to identify our volcanic rock specimens. To learn more about textures and mineralogy of igneous rocks follow on the them below.

- Igneous Rock Textures
- The Minerals of Igneous Rocks
- Classification of Igneous Rocks

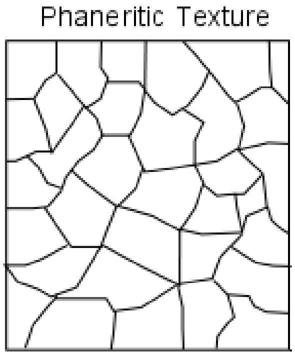
IGNEOUS ROCK TEXTURES

Phaneritic

Examples of Phaneritic Rocks (the three images below show a hand sample, low magnification of a hand sample and a thin section of phaneritic textured rocks)



Phaneritic textured rocks are comprised of large crystals that are clearly visible to the eye with or without a hand lens or binocular microscope. The entire rock is made up of large crystals, which are generally 1/2 mm to several centimeters in size; no fine matrix material is present. This texture forms by slow cooling of magma deep underground in the plutonic environment.



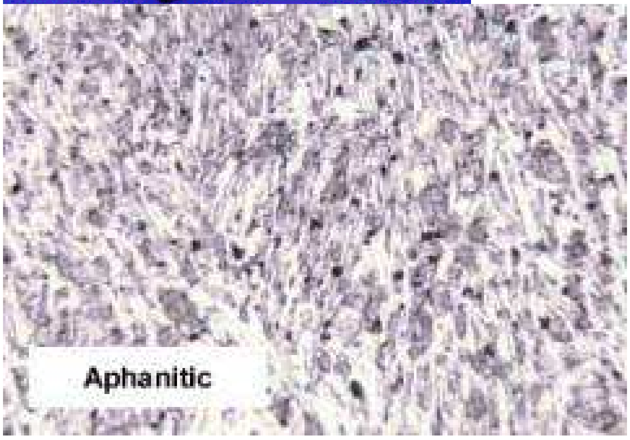
The cartoon sketch above, though highly idealized, attempts to make the point that in order to be truly phaneritic all of the mineral grains must be visible. The beginner often makes the mistake of identifying porphyritic textured (see discussion below) aphanitic rocks as phaneritic. For the more felsic rocks like granite, phaneritic texture is rarely misidentified. But dark rocks like gabbro are more problematic. A good rule of thumb is that fine grained or aphanitic rocks are dull appearing, while phaneritic rocks are brighter or shinier (of course be careful of a glassy rock like obsidian).

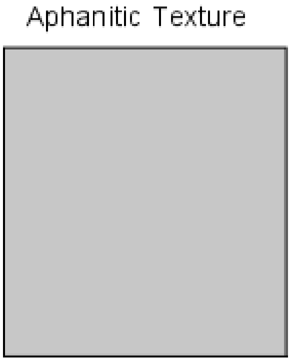
Examples of Phaneritic Rocks

Aphanitic Texture

Examples of Aphanitic Rocks (the two images below show a hand sample and a thin section of aphanitic textured rocks)

Aphanitic texture consists of small crystals that cannot be seen by the eye with or hand lens. The entire rock is made up of small crystals, which are generally less than 1/2 mm in size. This texture results from rapid cooling in volcanic or hypabyssal (shallow subsurface) environments.



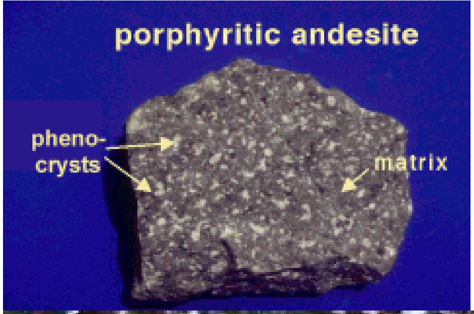


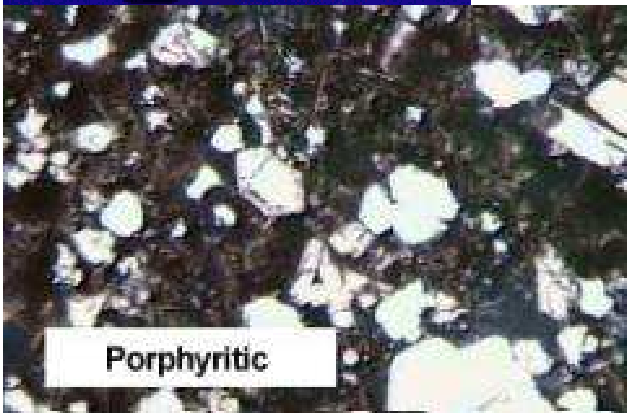
Yes, I know the cartoon above is rather crude, but it gets the point across. Aphanitic rocks are characterized by textures in which the mineral grains are not visible to the eye so they generally look rather like a blank slate. Of course, this represents an ideal world. Most aphanitic rocks will have at least a few phenocrysts (larger grains). This often causes the lay person to assume a phaneritic texture, but with a little practice you will find you can quickly distinguish between aphanitic and phaneritic textures.

Examples of Aphanitic Rocks

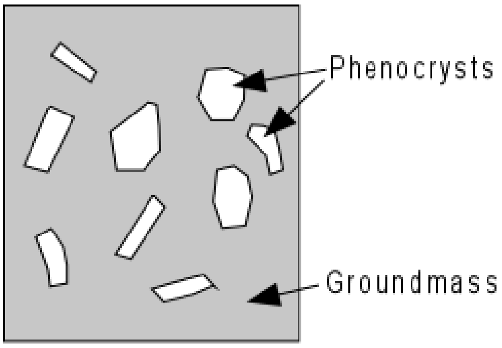
Porphyritic Texture

Porphyritic Rocks (the two images below show a hand sample and a thin section of porphyritic aphanitic textured rocks)





Porphyritic texture is really a subtype, but usage of the term often confuses the beginner. Porphyritic rocks are composed of at least two minerals having a conspicuous (large) difference in grain size. The larger grains are termed phenocrysts and the finer grains either matrix or groundmass (see the drawing below and image to the left). Porphyritic rocks are thought to have undergone two stages of cooling; one at depth where the larger phenocrysts formed and a second at or near the surface where the matrix grains crystallized.

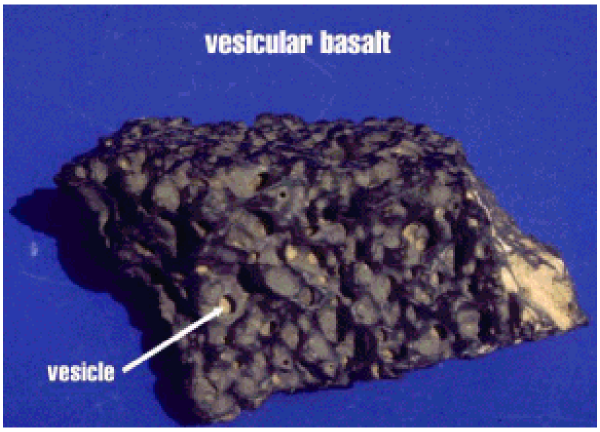


Both aphanitic and phaneritic rocks can be porphyritic, but the former are far more common. Most often the porphritic term is utilized as a modifier. For instance, an andesite with visible phenocrysts of plagioclase feldspar would be termed an andesite porphyry or porphyritic andesite (see photo above).

Glassy Texture

Glassy textured igneous rocks are non-crystalline meaning the rock contains no mineral grains. Glass results from cooling that is so fast that minerals do not have a chance to crystallize. This may happen when magma or lava comes into quick contact with much cooler materials near the Earth's surface. Pure volcanic glass is known as obsidian (see photo).

Vesicular Texture



This term refers to vesicles (holes, pores, or cavities) within the igneous rock. Vesicles are the result of gas expansion (bubbles), which often occurs during volcanic eruptions. Pumice and scoria are common types of vesicular rocks. The image to the left shows a basalt with vesicles, hence the name "vesicular basalt".

Fragmental Texture

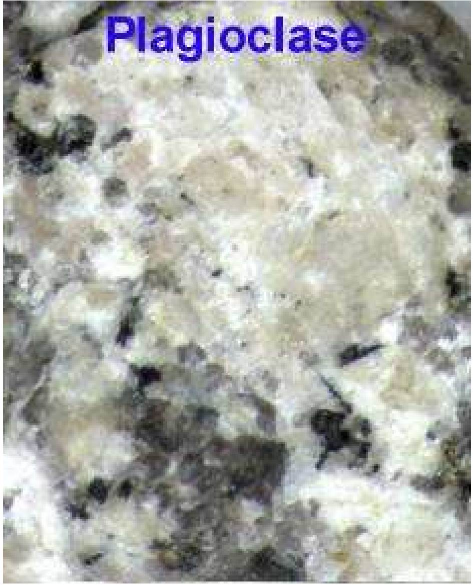
We are almost done, I promise. The last textural term is reserved for pyroclastic rocks, those blown out into the atmosphere during violent volcanic eruptiions. These rocks are collectively termed fragmental. If you examine a fragmental volcanic rock closely you can see why. You will note that it is comprised of numerous grains or fragments that have been welded together by the heat of volcanic eruption. If you run your fingers over the rock it will often feel grainy like sandpaper or a sedimentary rock. You might also spot shards of glass embedded in the rock. The terminology for fragmental rocks is voluminous, but most are simply identified as "tuff".

MINERALS OF IGNEOUS ROCKS

To correctly classify many igneous rocks it is first necessary to identify the constituent minerals that make up the rock. Piece of cake you say, I saw most of these minerals when I did the Minerals Exercise or I have them in my mineral collection. Well, its not quite that easy. The mineral grains in rocks often look a bit different than the larger mineral specimens you see in lab or museum collections. The following section is meant to assist you in recognizing common rock-forming minerals in igneous rocks. Refer back to it often as you attempt to classify your rock specimens.

Plagioclase

Plagioclase: the white or chalky looking grain is the common feldspar, plagioclase.



Plagioclase is the most common mineral in igneous rocks. The illustration to the left shows a large chalky white grain of plagioclase. The chalky appearance is a result of weathering of plagioclase to clay and this can often be used to aid in identification. Most plagioclase appears frosty white to gray-white in igneous rocks, but in gabbro it can be dark gray to blue-gray. If you examine plagioclase with a hand lens or binocular microscope you can often see the stair-step like cleavage and possibly striations (parallel grooves) on some cleavage faces. Some potassium feldspar is white like plagioclase, but is usually a safe bet to identify any frosty white grains in igneous rocks as plagioclase. Expect to find plagioclase in most phaneritic igneous rocks and often as phenocryts in aphanitic rocks.

Quartz

Quartz: the dark gray, glassy grain is quartz.

Quartz is also a very common mineral in some igneous rocks. It can be difficult to recognize since it doesn't look like the beautiful, clear hexagonal-shaped mineral we see in mineral collections or for sale in rock shops. In igneous rocks it is often medium to dark gray and has a rather amorphous shape. If you look at it with a hand lens you will notice the glassy appearance and lack of any smooth cleavage surfaces. You will also find quartz grains resist scratching with a nail or pocket knife, You can expect to find abundant quartz in granite and as phenocryts in the volcanic rock rhyolite. In some other common igneous rocks you may find a few scattered grains of quartz, but it is often conspicuous by its absence. Once recognized, quartz is rarely confused with any other common rock-forming mineral.

Potassium Feldspar

Orthoclase: the slightly pinkish grains are the potassium feldspar, orthoclase.

Think pink is the motto for potassium feldspar. The image to the left shows several large grains of the potassium feldspar, orthoclase; note the pinkish cast. As orthoclase is a feldspar, you should also see the stair-step cleavage characteristic of feldspars. Unfortunately, all potassium feldspar is not pink, microcline is usually white. How does one distinguish white potassium feldspar from plagioclase? The answer is that in hand samples it is nearly impossible. Sometimes striations on cleavage faces allow you to differentiate the two. Plagioclase has striations, potassium feldspar does not. But in most cases any white feldspar is identified as plagioclase and any pink feldspar as orthoclase. Expect to find orthoclase as a common constituent of granite and matrix material in rhyolite. In the latter rock the orthoclase is too fine-grained to be seen even with a binocular microscope, but its presence gives most rhyolites a distinct pinkish cast.

Muscovite

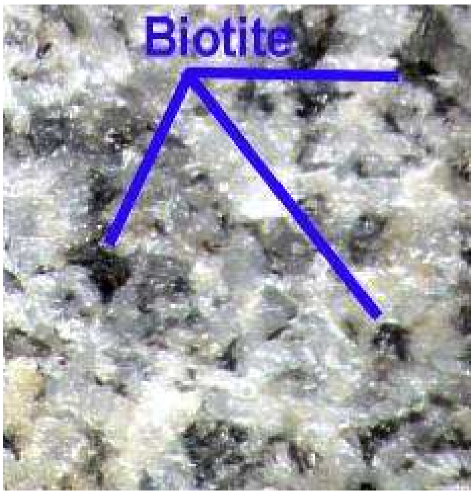
Muscovite: the small, shiny grains are muscovite.

Muscovite is not a common mineral in igneous rocks, but rather an accessory that occurs in small amounts. It is shiny and silvery, but oxidizes to look almost golden. In fact, more prospectors probably confused muscovite in their pans for gold than they did pyrite (fool's gold). Muscovite has excellent cleavage and will scratch easily. If you suspect muscovite is present, try taking a nail to it. It should flake off the rock. Muscovite occurs in some granites and occasionally in diorite. Unlike, its close cousin, biotite, it rarely occurs as phenocrysts in volcanic rocks.

Biotite

Biotite: the small, black grains are biotite.

Biotite occurs in small amounts in many igneous rocks. It is black, shiny and often occurs in small hexagonal (6-sided) books. Unfortunately, it is often confused with



amphibole and pyroxene. Like muscovite, it is soft and has good cleavage. Try scratching the black grains with a nail or knife. Biotite will flake off easily. Biotite is differentiated from amphibole by shape of the crystals (hexagonal for biotite and elongated or needle-like for amphibole) and by hardness (biotite is soft, amphibole is hard). It is differentiated from pyroxene by hardness, color (biotite is black and pyroxene dark green) and occurrence (biotite is found in light-colored igneous rocks like granites, diorites and rhyolites while pyroxene occurs in dark-colored rocks like gabbro and basalt). Expect to find biotite as a common accessory in granite, and as phenocrysts in some rhyolites.

Amphibole

Amphibole: the elongated, black grains are amphibole.

Amphibole is a rather common mineral in all igneous rocks, however, it is only abundant in the intermediate igneous rocks. It occurs as slender needle-like crystals (see image to the left). It has good cleavage in 2 directions and hence has a stair-step appearance under a binocular microscope. It is often confused with biotite and pyroxene. Biotite is softer and the needle-like crystals differentiate it from pyroxene. One caution, most students believe that all amphibole crystals must have the pencil-like appearance. Remember the orientation of grains in an igneous rock is random. What would your pencil look like if you looked at it down the eraser? Not all grains of amphibole will be oriented so you can see the elongation of the crystals. Its a good guess that if you see a few crystals that have the "classic" amphibole shape, the other black grains are also amphibole. Biotite and amphibole do occur together in igneous rocks, but the association is not all that common. Amphibole is very commom in diorite, less so in granite or gabbro. It also is a common and diagnostic phenocryst in andesite.

Pyroxene

Pyroxene: the equi-dimensional, green grains are pyroxene.

Pyroxene is common only in mafic igneous rocks. It occurs as short, stubby, dark green crystals (see image to the left). It has poor cleavage in 2 directions and cleavage surfaces are often hard to see with even a binocular microscope. It is often confused with biotite and amphibole. Biotite is softer, darker and occurs in predominantly light-colored rocks Amphibole is also darker and occurs in needle-like crystals rather than the stubby shape of pyroxene. Association is the best guide for the identification of pyroexene. It is usually restricted to dark-colored rocks (the image on the left is of pyroxene is a very rare light-colored rock called shonkenite) such as gabbro or basalt.

Olivine

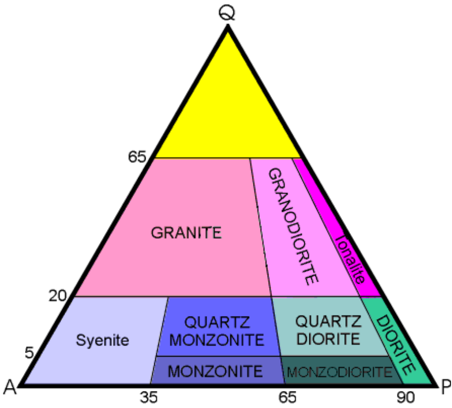
Olivine: the green, glassy grains are olivine.

Olivine is common only in ultramafic igneous rocks like dunite and peridotite. It occurs as small, light green, glassy crystals (see image to the left). It has no cleavage. The texture of olivine in igneous rocks is often termed sugary. Run your fingers over the grains, do they feel like sandpaper? The mineral is most probably olivine. Although olivine occurs in gabbro and basalt, it is far more common in peridotite and dunite. Because of the light green color and sugary texture it is rarely confuded with other rock-forming minerals.

CLASSIFICATION
OF IGNEOUS ROCKS

The classification of igneous rocks has been the subject of frequent debate and voluminous literature. Over the past decade, most geologists have accepted the IUGS (International Union of the Geological Sciences) classification as the standard. Since this classification is being widely adopted, it bears discussion. However, as we shall see is rather complex and best left to advanced students. For our purposes, we will introduce and discuss a much simpler classification that will allow us to easily identify the more common igneous rocks.

IUGS Classification



Highly Modified IUGS Classification
of Phaneritic Igneous Rocks

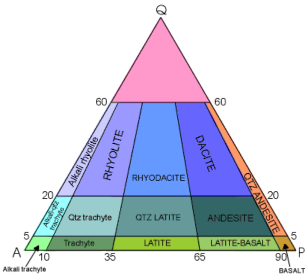
Why Do We Need to Classify Things?

Carolus Linneaus proposed the first classifcation for biological organisms in the 18th century. This taxonomic classification was designed to simplify the complexity of nature by lumping together living species that shared common traits. So to classifications in the earth sciences are designed to reduce complexity. For instance, the classification of minerals is based on common anoins since minerals sharing common anions often have similar physical properties (i.e hardness, cleavage etc.). Rock classifications also seek to reduce complexity. Most are what we term genetic. That means that by pigeonholing a rock in a certain group we say something about its genesis or origin. For example, aphanitic rocks are or volcanic origin while phaneritic rocks are plutonic.

Igneous rocks are classified on the basis of mineralogy, chemistry, and texture. As discussed earlier, texture is used to subdivide igneous rocks into two major groups: (1) the plutonic rocks, with mineral grain sizes that are visible to the naked eye, and (2) the volcanic rocks, which are usually too fine-grained or glassy for their mineral composition to be observed without the use of a petrographic microscope. As noted in the sidebar to the left, this is largely a genetic classification based on the depth of origin of the rock (volcanic at or near the surface, and plutonic at depth). Remember that porphyritic rocks have spent time in both worlds. Let's first examine the classification of plutonic rocks.

A plutonic rock may be classified mineralogically based on the actual proportion of the various minerals of which it is composed (called the mode). In any classification scheme, boundaries between classes are set arbitrarily. The International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Igneous Rocks in 1973 suggested the use of the modal composition for all plutonic igneous rocks with a color index less than 90 (Image to the right). A second scheme (not shown) was proposed for those plutonic ultramafic rocks with a color index greater than 90.

The plotting of rock modes on these triangular diagrams is simpler than it may appear. The three components, Q (quartz) + A (alkali (Na-K) feldspar) + P (plagioclase), are recalculated from the mode to sum to 100 percent. Each component is represented by the corners of the equilateral triangle, the length of whose sides are divided into 100 equal parts. Any composition plotting at a corner, therefore, has a mode of 100 percent of the corresponding component. Any point on the sides of the triangle represents a mode composed of the two adjacent corner components. For example, a rock with 60 percent Q and 40 percent A will plot on the QA side at a location 60 percent of the distance from A to Q. A rock containing all three components will plot within the triangle. Since the sides of the triangle are divided into 100 parts, a rock having a mode of 20 percent Q and 80 percent A + P (in unknown proportions for the moment) will plot on the line that parallels the AP side and lies 20 percent of the distance toward Q from the side AP. If this same rock has 30 percent P and 50 percent A, the rock mode will plot at the intersection of the 20 percent Q line described above, with a line paralleling the QA side at a distance 30 percent toward P from the QA side. The third intersecting line for the point is necessarily the line paralleling the QP side at 50 percent of the distance from the side QP toward A. A rock with 25 percent Q, 35 percent P,



IUGS Classification of Volcanic Rocks

and 40 percent A plots in the granite field, whereas one with 25 percent Q, 60 percent P, and 15 percent A plots in the granodiorite field. The latter is close to the average composition of the continental crust of the Earth.

Ideally it would be preferable to use the same modal scheme for volcanic rocks. However, owing to the aphanitic texture of volcanic rocks, their modes cannot be readily determined; consequently, a chemical classification is widely accepted and employed by most petrologists. One popular scheme is based on the use of both chemical components and normative mineralogy. Because most lay people have little access to analytic facilities that yield igneous rock compositions, only an outline will be presented here in order to provide an appreciation for the classification scheme.

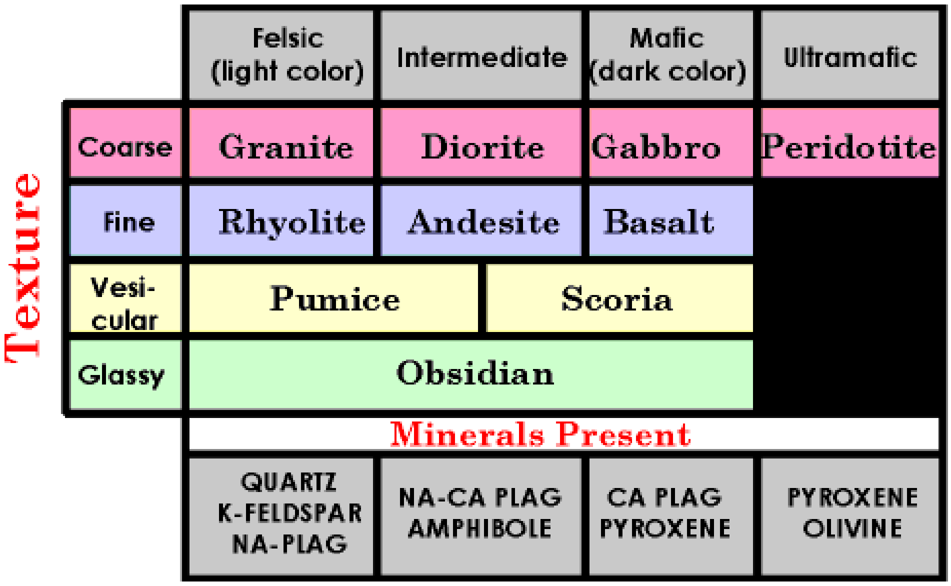
The major division of volcanic rocks is based on the alkali (soda + potash) and silica contents, which yield two groups, the subalkaline and alkaline rocks. Furthermore as they are so common, the subalkaline rocks have two divisions based mainly on the iron content with the iron-rich group called the tholeiitic series and the iron-poor group called calc-alkaline. The former group is most commonly found along the oceanic ridges and on the ocean floor and is usually restricted to mafic igneous rocks like basalt and gabbro; the latter group is characteristic of the volcanic regions of the continental margins (convergent, or destructive, plate boundaries) and is comprised of a much more diverse suite of rocks.

Chemically the subalkaline rocks are saturated with respect to silica. This chemical property is reflected in the mode of the mafic members that have two pyroxenes, hypersthene and augite [Ca(Mg, Fe)Si2O6], and perhaps quartz. Plagioclase is common in phenocrysts, but it can also occur in the matrix along with the pyroxenes. In addition to the differences in iron content between the tholeiitic and calc-alkaline series, the latter has a higher alumina content (16 to 20 percent), and the range in silica content is larger (48 to 75 percent compared to 45 to 63 percent for the former). Hornblende and biotite phenocrysts are common in calc-alkaline andesites and dacites but are lacking in the tholeiites. Dacites and rhyolites commonly have phenocrysts of plagioclase, alkali feldspar (usually sanidine), and quartz in a glassy matrix. Hornblende and plagioclase phenocrysts are more widespread in dacites than in rhyolites, which have more biotite and alkali feldspar.

The alkaline rocks typically are chemically undersaturated with respect to silica; hence, they have only one pyroxene, the calcium-rich augite) and lack quartz but often have a feldspathoid mineral, nepheline. Microscopic examination of alkali olivine basalts (the most common alkaline rock) usually reveals phenocrysts of olivine, one pyroxene (augite), plagioclase and perhaps nepheline.

A Field Classification

Now that we have completely confused you,let's look at a much simpler classification. We call this a *field classification* because it requires little detailed knowledge of rocks and can be easily applied to any igneous rock we might pick up while on a field trip. It utilizes texture, mineralogy and color. The latter is a particularly unreliable property, but the classification realizes that certain fine-grained (aphanitic) igneous rocks contain no visible mineral grains and in their absence color is the only other available property. Students the thus cautioned to use color only as a last resort.



Texture	Felsic (light color)	Intermediate	Mafic (dark color)	Ultramafic
Coarse	Granite	Diorite	Gabbro	Peridotite
Fine	Rhyolite	Andesite	Basalt	
Vesi-cular	Pumice	Scoria		
Glassy	Obsidian			
	Minerals Present			
	QUARTZ K-FELDSPAR NA-PLAG	NA-CA PLAG AMPHIBOLE	CA PLAG PYROXENE	PYROXENE OLIVINE

To employ this classification we must first determine the rock's texture. You might remember we have five basic textures; phaneritic (coarse), aphanitic (fine), vesicular, glassy and fragmental (our classification doesn't bother with the latter because we often term all fragmental igneous rocks tuffs). Examine your rock and determine which textural group it belows to. If it is glassy, vesicular or fragmental you cannot determine mineralogy and hence the name is simply obsidian for a glass, tuff for a fragmental or pumice/scoria for a vesicular rock (the latter are differentiated on the basis or color and size of the vesicles or holes).

For the phaneritic and some aphanitic rocks you must determine the mineralogy. Often it is only necessary to identify one or two key minerals, not all of the minerals in the rock. For instance quartz and potassium feldspar (k-feldspar) are restricted to granites and rhyolites. Amphibole is only abundant in diorite or andesite, although minor amounts can be present in granite. How am I getting these names? Let's take an example. I pick up my first specimen and notice that it is distinctly coarse grained (phaneritic). This means that it must be one of the rocks in the row labeled *coarse* (i.e., granite, diorite, gabbro or peridotite). I next place the rock under a binocular microscope and identify the minerals plagioclase and pyroxene. I go to the bottom row of the chart (Minerals Present) and look for a match with my mineralogy. I find it in the third column (Ca-play, pyroxene) and read the name (gabbro) from the *coarse* row on the chart. Pretty simple!! Relax, when you actually begin your igneous rock identification we will walk you through it step by step. But remember to refer to the above classification diagram often as an aid.

Identification steps

Step 1

The first step involves determining the texture of your unknown rock sample. There are five basic textural types, phaneritic, aphanitic, glassy, vesicular and fragmental. Examples of each are shown below. Remember, many rocks have a porphyritic texture (two different grain sizes). But in reality, we treat porphyritic textured rocks as either phaneritic or aphanitic depending on size of the smallest of the two different grain sizes. Most porphyritic textures rocks end up in the aphanitic group, but rarely we do see a porphyritic phaneritic rock. Let's examine your rock. CLICK on the appropriate texture to move to the next identification step.

Phaneritic (coarse-grained) texture. All of the mineral grains should be visible with the unaided eye.

Texture - Phaneritic (coarse grained)

Step 2

The identification of phaneritic-textured igneous rocks involves a second step, determining the mineralogy. To help you with the process review the discussion of Igneous Minerals. The table below lists the minerals you may find in each of the common phaneritic igneous rocks. The key or important minerals for identification purposes are in BOLD and ALL CAPS. Some rocks will not have all of the minerals listed, but all should have at least one of the important or diagnostic minerals. If your sample does not appear to have a phaneritic texture or any of the minerals below. Go Back to the previous step.

COLOR	MINERALOGY
Light colored, pink or white	QUARTZ, POTASSIUM FELDSPAR plagioclase, biotite, muscovite, amphibole
Intermediate color, dark pink or gray	AMPHIBOLE, plagioclase
Dark color, dark gray or black	PYROXENE, plagioclase, olivine
Light green color	OLIVINE, pyroxene

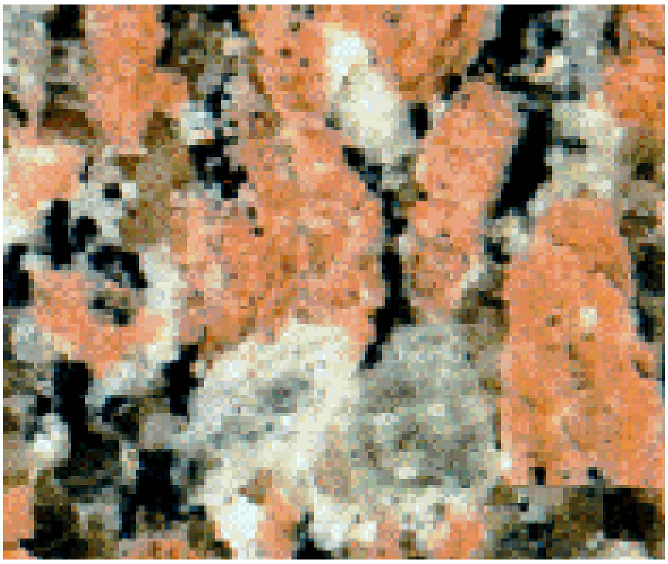
Light colored,pink or white:

Texture - Phaneritic

Variable color, pink to white, can be light gray	Quartz and/or orthoclase (k-feldspar); plagioclase, minor biotite, amphibole and muscovite may be present	

Your Rock is Granite!

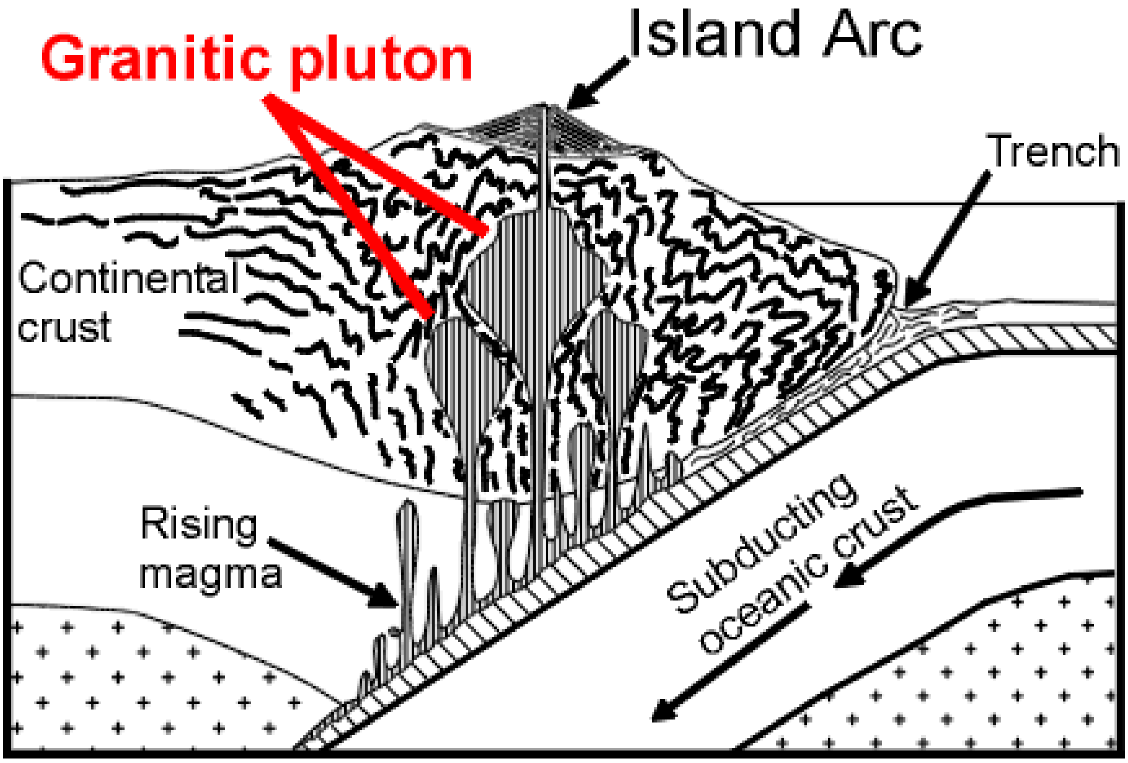
GRANITE



Granite is a coarse or medium-grained intrusive igneous rock that is rich in quartz and feldspar (k-feldspar and plagioclase); it is the most common plutonic rock of the Earth's crust, forming by the cooling of magma (silicate melt) at depth.

Granite has found its biggest use as paving block and as a building stone. The quarrying of granite was, at one time, a major mining activity in the New England and southeastern states. Today, except for tombstones, for which there is a continuing demand, the production of granite is geared to the fluctuating market for highway construction and veneer or sheet rock used in the facing of large commercial buildings.

Granite may occur in dikes or sills (tabular bodies injected in fissures and inserted between other rocks), but more characteristically it forms irregular masses of extremely variable size, ranging from less than a few square miles to larger masses (batholiths) that are often hundreds or thousands of square miles in area.



The principal constituent of granite is feldspar. Both plagioclase feldspar and potassium feldspar are usually abundant in it, and their relative abundance has provided the basis for granite classifications. In most granite, the ratio of the dominant to the subdominant feldspar is less than two. This includes most granites from the eastern, central, and southwestern United States. Granites in which plagioclase greatly exceeds potassium feldspar are common in large regions of the western United States and are thought to be characteristic of the great series of batholiths stretching from Alaska and British Columbia southward through Idaho and California into Mexico. Granites with a great excess of potassium feldspar over plagioclase are known from New England, but their most extensive development is in Nigeria.

Rocks containing less than 20 percent quartz are almost never named granite, and rocks containing more than 20 percent (by volume) of dark, or ferromagnesian, minerals are also seldom called granite. The minor essential minerals of granite may include muscovite, biotite, amphibole, or pyroxene. Biotite may occur in granite of any type and is usually present, though sometimes in very small amounts.

Granitic magmas are generated at convergent plate boundaries where the oceanic lithosphere (the outer layer of the Earth composed of the crust and upper mantle) is subducted so that its edge is positioned below the edge of the continental plate or another oceanic plate. Heat will be added to the subducting lithosphere as it moves slowly into the hotter depths of the mantle. This will cause the overlying wedge of crustal material to melt. The formation of granite is often envisioned as a two-stage process. The first stage involves partial melting of lower crust and perhaps subducted oceanic material to form a magma of andesitic composition (see discussion of andesite). The produces island arcs and volcanic mountain chains comprised of andesite and diorite. The base of these andesite/diorite piles then, in turn, partially melts to form magmas of granitic composition

Intermediate color, dark pink or gray:

Texture - Phaneritic

Black and white (spotted)	Amphibole very abundant, plagioclase common, about a 50:50 mix of light and dark minerals Your Rock is Diorite!	

DIORITE

Diorite is a medium to coarse-grained intrusive igneous rock that commonly is composed of about two-thirds plagioclase feldspar and one-third dark-colored minerals, such as amphibole and/or biotite. The presence of sodium-rich feldspar, oligoclase or andesine, in contrast to calcium-rich plagioclase, labradorite or bytownite, is the main distinction between diorite and gabbro. The extrusive (volcanic) equivalent of diorite is andesite.

Diorite has about the same structural properties as granite but, perhaps because of its darker colour and more limited supply, is rarely used as an ornamental and building material. It is one of the dark gray rocks that is sold commercially as black granite.

Most diorites are truly igneous; they have crystallized from molten material (magma). Occassionally, we find others that are products of reactions between magma and included fragments of foreign rock (xenoliths). Many have been chemically transformed (metasomatized) in the solid state from some pre-existing rock, such as gabbro, by the loss of certain constituent atoms and the gain of others.

Diorite occurs in small bodies such as sills (tabular bodies inserted while molten between other rocks), dikes (tabular bodies injected in fissures), stocks (bodies intruded upward), or as more irregular masses associated with gabbro. More commonly it occurs in batholiths (huge bodies) with granodiorite and granite. The igneous rock of the San Gabriel Mountains of southern California is predominantly diorite.

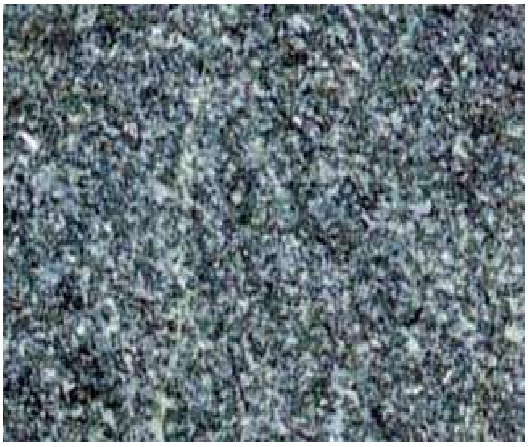
Diorite, and its volcanic equivalent andesite, are thought to be the be the initial products of plate subduction at convergent margins. Indeed, huge bodies of diorite and granodiorite form the core of the Sierra Nevadas. Radiometric age dating of batholiths has shown that diorite is consistently older than adjacent granites supporting a model which has granitic plutons being emplaced after diorite. This model suggests that subducted basaltic crust is partially melted and may be combined with some subducted oceanic sediments to form andesites/diorites. Diorite is then partially melted to generate the younger granitic magmas.

Dark color, dark gray or black:

Texture - Phaneritic

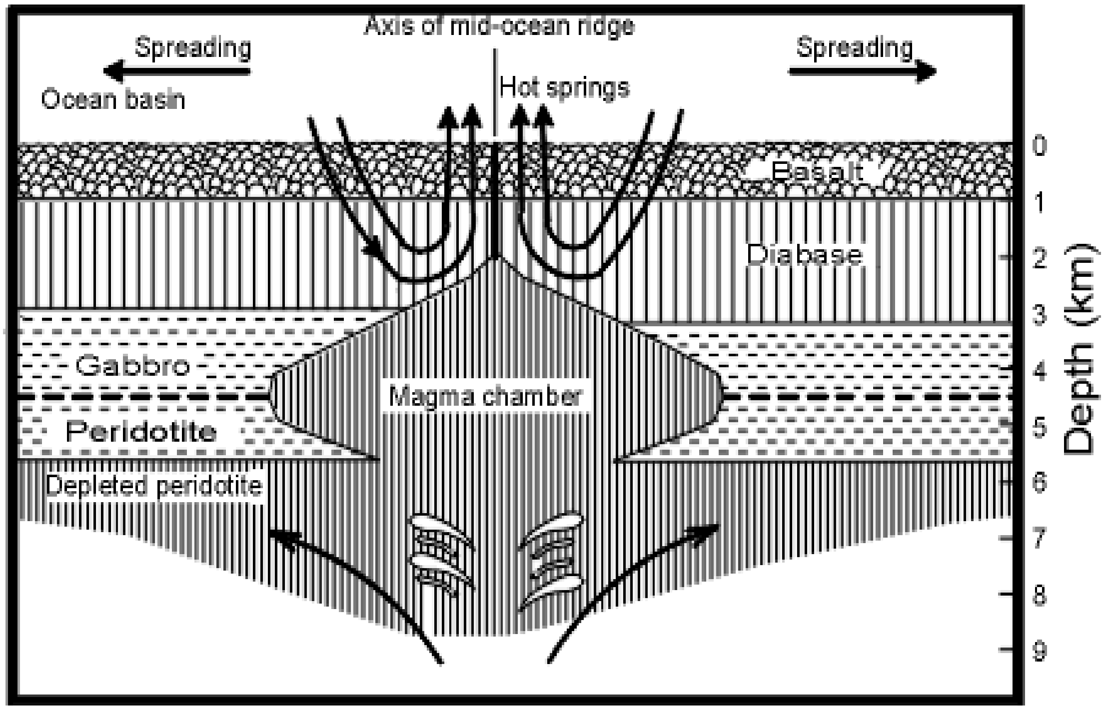
Very dark gray to black	Pyroxene very abundant, plagioclase common, may appear rusty on weathered surfaces	

Your Rock is Gabbro!



GABBRO

Gabbro is a medium or coarse-grained rock that consists primarily of plagioclase feldspar and pyroxene. Essentially, gabbro is the intrusive (plutonic) equivalent of basalt, but whereas basalt is often remarkably homogeneous in mineralogy and



composition, gabbros are exceedingly variable. Gabbros are found widely on the Earth and on the Moon as well. Gabbros are sometimes quarried for dimension stone (the black granite of commerce), and the San Marcos Gabbro of southern California is used for gauge blocks, but the true economic value of gabbro is minor. Far more important are the nickel, chromium, and platinum that occur almost exclusively in association with gabbroic or related ultramafic rocks. Primary magnetite (iron) and ilmenite (titanium) mineralizations are often intimately associated with gabbroic complexes.

Banded, or layered, gabbroic complexes in which monomineral or bimineral varieties are well developed have been described from Montana, the Bushveld in South Africa, and the island of Skye. There are also gabbro complexes that are inhomogeneous and not regularly layered, as the large, basinlike intrusion at Sudbury, Ontario, and some of the larger diabase sills (tabular intrusions), as the Palisades, New Jersey; and many of the Karoo diabases (fine-grained gabbro) in South Africa. A lopolith at Duluth, Minn., is a notable exception to the rather arbitrary division between layered and unlayered gabbro complexes. The lower part of this mass has the average composition of an olivine gabbro but is strongly banded. The upper portion is a comparatively homogeneous feldspathic gabbro, not sharply banded.

Although gabbro forms in diverse tectonic settings, much is thought to form at divergent plate margins. Here, the gabbro is a product of mantle-derived partial melts of peridotite. These partial melts rise bouyantly in the oceanic crust and solidify. The upper portion of the magma chamber crystallizes as the fine-grained, ubiquitous, pillow lavas characteristic of the ocean floor, while the middle and lower portions of the system soldify as diabasic dikes and cumulus textured gabbro.

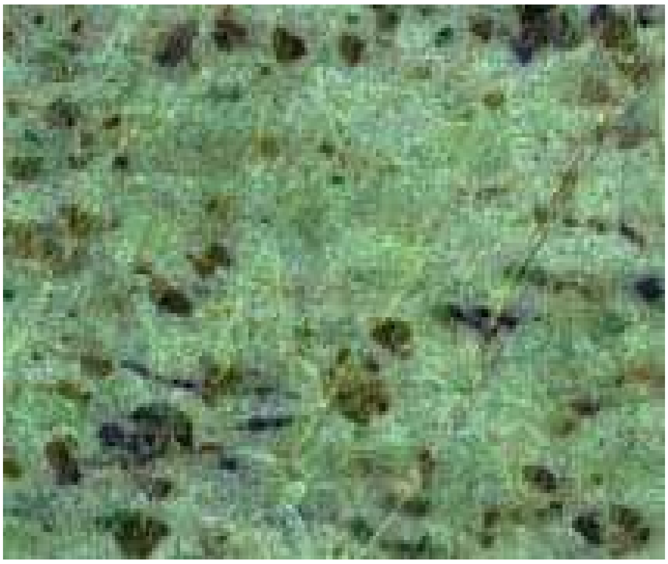
Light green color:

Texture - Phaneritic

Green	Olivine very abundant, pyroxene may be present	

Your Rock is Peridotite!

PERIDOTITE



Peridotite is a medium-grained, dark-colored, intrusive igneous rock that contains at least 10 percent olivine, other iron- and magnesium-rich minerals (generally pyroxenes), and not more than 10 percent feldspar. It occurs in four main geologic environments: (1) interlayered with other ultramafic rocks in the lower parts of layered igneous complexes or masses; (2) in alpine-type mountain belts as irregular, olivine-rich masses, with or without related gabbro; (3) in volcanic pipes (funnels, more or less oval in cross section, that become narrower with increasing depth) as kimberlite; and (4) as dikes and irregular masses with rocks exceptionally rich in potassium and sodium. The layered complexes are believed to have been formed in place by crystal settling from a previously intruded fluid or magma. Other types seem to have ranged from fluid magmas to semisolid crystal mushes at the time of emplacement like kimberlites.

Peridotite is the source of all chromium ore and naturally occurring diamonds, and of nearly all chrysotile asbestos. It is one of the main host rocks of talc deposits and platinum metals and formerly was a major source of magnesite. Fresh dunite (olivine-rock) is used in parts of glass furnaces. Nearly all peridotite is more or less altered to serpentine (hydrous phases are present) In warm, humid climates peridotite and serpentine have weathered to soils worked on a relatively small scale for iron, nickel, cobalt, and chromium.

Based on the observed samples, peridotite with about 50 percent olivine, 30 percent pyroxene, and 15 percent garnet is considered to be the dominant rock of the upper mantle. This conclusion is supported by melting studies that demonstrate that a basaltic liquid is produced if peridotite is heated enough to melt partially. It is by partial melting of the upper mantle beneath mid-oceanic ridges that the basalt and gabbro composing the oceanic crust is produced. The effect of this partial melting is to slightly deplete the original peridotite in aluminum and iron that preferentially are concentrated into the basaltic liquid. Thus, when aluminum and iron-rich xenoliths are present in a peridotite, they are referred to as "fertile," meaning that they have not yet been significantly melted and could produce basaltic liquid upon partial melting.

Aphanitic (fine-grained) texture. Most or all of the mineral grains cannot be seen with the unaided eye.

Texture - Aphanitic (fine grained)

Step 2

The identification of aphanitic-textured igneous rocks can often be frustrating. When no minerals are visible we have to rely on color, a poor means of identifying a rock. When a few mineral grains are present as phenocrysts in a fine-grained matrix, these can be very helpful in the identification. The table below lists the minerals you may find in each of the common aphanitic igneous rocks and their approximate colors. If your sample does not appear to have an aphanitic texture or any of the minerals below. Go Back to the previous step.

COLOR	MINERALOGY
Pink or white	Quartz, Potassium feldspar
Light to medium gray, or red-purple	Amphibole, Plagioclase
Dark gray or black	Pyroxene, Olivine

Pink or white:

Texture - Aphanitic

White to distinctly pink	Often contains phenocrysts or quartz or potassium feldspar	

Your Rock is Rhyolite!

RHYOLITE

Rhyolite is extrusive igneous rock that is the volcanic equivalent of granite. Most rhyolites are porphyritic, indicating that crystallization began prior to extrusion. Crystallization may sometimes have begun while the magma was deeply buried; in such cases, the rock may consist principally of well-developed, large, single crystals (phenocrysts) at the time of extrusion. The amount of microcrystalline matrix (groundmass) in the final product may then be small. In most rhyolites, however, the period of such crystallization is relatively short, and the rock consists largely of a microcrystalline or partly glassy matrix containing a few phenocrysts. The glassy rhyolites include obsidian, pitchstone, perlite, and pumice.

The chemical composition of rhyolite is very like that of granite. The phenocrysts of rhyolite may include quartz, potassium feldspar, plagioclase feldspar, biotite, amphibole, or pyroxene. Certain differences between rhyolite and granite are noteworthy. Muscovite, a common mineral in granite, occurs very rarely and only as an alteration product in rhyolite. In most granites the potassium feldspar is microcline or microcline-perthite; in most rhyolites, however, it is sanidine. A great excess of potassium over sodium, uncommon in granite except as a consequence of hydrothermal alteration, is not uncommon in rhyolites.

Rhyolites are known from all parts of the Earth and from all geologic ages. They are mostly confined, like granites, to the continents or their immediate margins, but they are not entirely lacking elsewhere. Small quantities of rhyolite have been described from oceanic islands remote from any continent. An unusual occurrence of rhyolite has been observed in the Mojave Desert. There the rhyolite occurs in bimodal volcanic fields comprised of basalt and rhyolite. An absence of the intermediate volcanic rock, andesite, suggests these two rock types had separate origins and their parent magmas did not mix. The origin of these bimodal fields remains the subject of much study and conjecture.

Light to medium gray, or red-purple:

Texture - Aphanitic

Light to medium gray	Abundant amphibole phenocrysts can be diagnostic when present, plagioclase can also be present but is NOT diagnostic	

Your Rock is Andesite!

ANDESITE

Andesite is common in most of the world's volcanic areas. Andesites occur mainly as surface deposits and, to a lesser extent, as dikes and small plugs. Not only the Andes, where the name was first applied to a series of lavas, but most of the cordillera (parallel mountain chains) of Central and North America consist largely of andesites. The same rock type occurs in abundance in volcanoes along practically the entire margin of the Pacific Basin. The volcanoes Montagne Pel馥, the Soufri鑽e of St. Vincent, Krakatoa, Bandai-san, Popocat駱etl, Fuji, Ngauruhoe, Shasta, Hood, and Adams have emitted great quantities of andesitic lava.

Andesite most commonly is fine-grained, usually porphyritic. In composition, andesites correspond roughly to the intrusive igneous rock diorite and consist essentially of andesine (a plagioclase feldspar) and one or more ferromagnesian minerals, usually amphibole or biotite. The larger crystals of feldspar and ferromagnesian minerals are often visible to the naked eye; they lie in a finer groundmass, usually crystalline, but sometimes glassy. There are three subdivisions of this rock family: the quartz-bearing andesites, or dacites, sometimes considered to be a separate family; the hornblende- and biotite-andesites; and the pyroxene-andesites.

Andesite forms at convergent plate margins and is thought to be the product of partial melts of the water-rich subducting oceanic crustal basalts or of the intervening wedge of lower crustal rocks above the subducting plate. While andesite is common in younger arc systems such as the Cascades, it is nearly absent in the older Sierra Nevadas, possibly a consequence of erosion.

Texture - Aphanitic

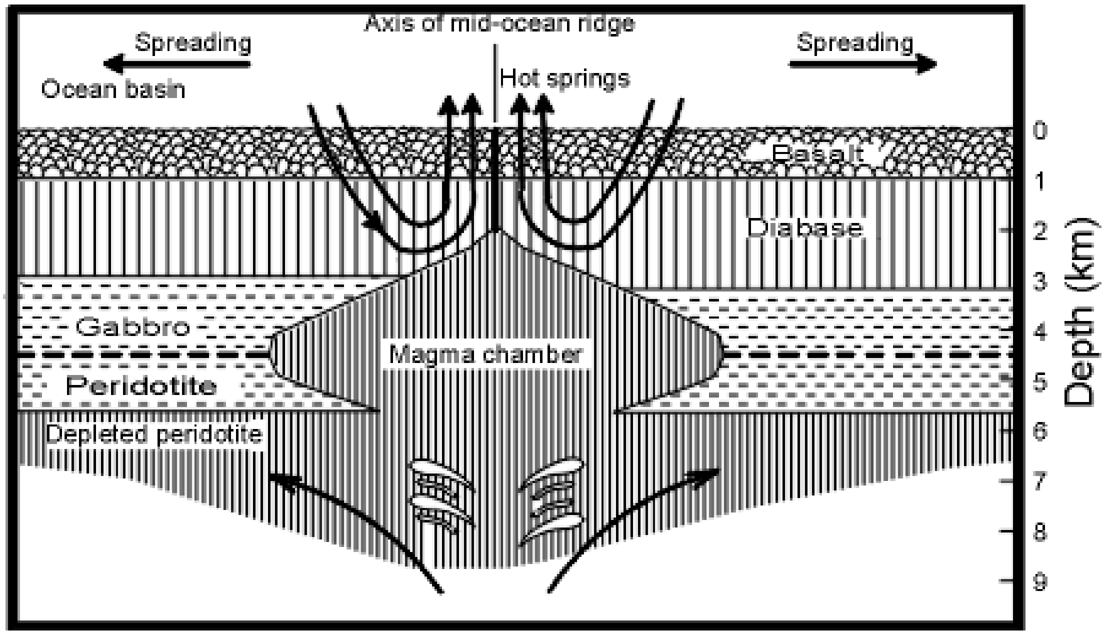
Very dark gray to black	Olivine phenocrysts may be present, but often color is the only means of identification	

Your Rock is Basalt!

BASALT

Basalt is an extrusive igneous rock that is low in silica content, dark in color, and comparatively rich in iron and magnesium.

Some basalts are quite glassy, and many are very fine-grained and compact; it is more usual, however, for them to exhibit porphyritic structure, with larger crystals (phenocrysts) of olivine, pyroxene, or feldspar in a finely crystalline matrix (groundmass). Olivine and pyroxene are the most common porphyritic minerals in basalts although plagioclase feldspar is also found. Basaltic lavas are frequently spongy or pumiceous; the steam cavities become filled with secondary minerals such as calcite, chlorite, and zeolites.



Because basalts are so abundant they are subdivided on a chemical and petrographic basis into two main groups: tholeiites and the alkali basalts. Tholeiitic basaltic lavas are characterized by plagioclase with the pyroxenes augite, pigeonite or hypersthene. They predominate among the lavas of mountain belts; their flows may build enormous plateaus, as in the northwestern United States, the Deccan of India, and the Paraná Basin of South America. The active volcanoes of Mauna Loa and Kilauea in Hawaii erupt tholeiitic lavas. Alkali basalt contains olivine and, commonly, a the pyroxenes diopside or titaniferous augite. Alkali basalts predominate among the lavas of the ocean basins (divergent plate margins as pillow lava) and are common among the basic lavas of the forelands and backlands of the mountain belts.

Minerals of the feldspathoid group occur in a large number of basaltic rocks belonging to the alkali group; nepheline, analcime, and leucite are the commonest. If nepheline entirely replaces feldspar, the rock is known as nepheline-basalt; if the replacement is only partial the term nepheline-basanite is used. Similarly, there are analcime- and leucite-basalts and leucite-basanites. Most nepheline-basalts are fine-grained, very dark-colored rocks and are of Tertiary age. They are fairly common in some parts of Germany and also occur in the United States (as in New Mexico). Leucite-basalts are found principally in Italy, Germany, eastern Africa, Australia, and, in the United States, in Montana, Wyoming, and Arizona. Basalts rich in feldspathoidal minerals such as nepheline and leucite are of uncertain origin. While they occur in ocean basins, they are much more common in continental settings suggesting the continental crust is enriching these basaltic magmas in alkalis and perhaps alumina.

Glassy texture. No mineral grains are present, the rock is comprised entirely of glass.

Texture - Glassy

Step 2

The identification of glassy rocks is quite easy. There is only one! First examine your rock for signs of concoidal fracture. It should be very apparent. Your glass should also be massive, not granular. Furthermore, most volcanic glass has a distinctly dark gray or black tint. If your sample does not match this description, Go Back to the previous step.

Fracture

When bonds between atoms are approximately the same in all directions within a mineral, breakage occurs either on irregular surfaces (splintery or irregular fracture) or along smooth, curved surfaces (conchoidal fracture), similar to those formed when thick pieces of glass are broken.

Glassy, black, concoidal fracture:

Texture - Glassy

Massive, shiny	Glass-like; concoidal fracture dark gray/black	

Your Rock is Obsidian!

OBSIDIAN

Obsidian is a natural glass of volcanic origin that is formed by the rapid cooling of viscous lava. Obsidian is extremely rich in silica, low in water, and has a chemical composition similar to rhyolite. Obsidian has a glassy luster and is slightly harder than window glass. Though obsidian is typically jet-black in color, the presence of hematite (iron oxide) produces red and brown varieties, and the inclusion of tiny gas bubbles may create a golden sheen. Other types with dark bands or mottling in gray, green, or yellow are also known.

Obsidian generally contains less than 1 percent water by weight. Under high pressure at depth, rhyolitic lavas may contain up to 10 percent water, which helps to keep them fluid even at a low temperature. Eruption to the surface, where pressure is low, permits rapid escape of water and increases the viscosity of the melt. Increased viscosity impedes crystallization, and the lava solidifies as a glass.

Different obsidians are composed of a variety of crystalline materials. Their abundant, closely spaced crystallites (microscopic embryonic crystal growths) are so numerous that the glass is opaque except on thin edges. Many samples of obsidian contain spherical clusters of radially arranged, needlelike crystals called spherulites. Microlites (tiny polarizing crystals) of feldspar and phenocrysts of quartz may also be present.

Obsidian was used by American Indians and many other primitive peoples for weapons, implements, tools, and ornaments and by the ancient Aztecs and Greeks for mirrors. Because of its conchoidal fracture (smooth curved surfaces and sharp edges), the sharpest artifacts were fashioned from obsidian; some of these, mostly arrowheads, have been dated by means of the hydration rinds that form on their exposed surfaces through time. Obsidian in attractive and its variegated colors make it useful as a semiprecious stone.

Vesicular texture. No mineral grains are present, the rock is light-weight and contains numerous holes or cavities.

Texture - Vesicular

Step 2

Actually any igneous rock can be vesicular (have gas holes in it). But two types of vesicular igneous rocks are so common we give them special names. Both are light weight. They are differentiated on the basis of color and the size of the holes or vesicules. If your sample is not light weight with abundant vesicles, Go Back to the previous step

Dark colored, light weight,vesicles are large and obvious:

Texture - Vesicular

Large vesicles or holes	Dark colored; thick-walled, abundant vesicles, light weight	

Your Rock is Scoria!

SCORIA

Scoria is a light-weight, dark-colored, glassy, pyroclastic igneous rock that contains many vesicles (bubblelike cavities). Foamlike scoria, in which the bubbles are very thin shells of solidified basaltic magma, occurs as a product of explosive eruptions (as on Hawaii) and as frothy crusts on some pahoehoe (smooth- or billowy-surfaced) lavas. Other scoria, sometimes called volcanic cinder, resembles clinkers, or cinders from a coal furnace.

The darker color of scoria has made it less useful commercially than pumice. Locally, it has been quarried for road cinders. US Highway 395 through the southern Owens Valley has been surfaces with scoria cinders from Red Hill, a small cinder cone adjacent to the highway.

Light colored, light weight,vesicles are quite small and may require a hand lens to be seen :

Texture - Vesicular

Small vesicles or holes	Light colored; thin-walled, abundant small vesicles, very light weight	

Your Rock is Pumice!

PUMICE

Pumice is a very porous, frothlike volcanic glass that has long been used as an abrasive in cleaning, polishing, and scouring compounds. It is also employed as a lightweight aggregate in precast masonry units, poured concrete, insulation and acoustic tile, and plaster.

Pumice is pyroclastic igneous rock that was almost completely liquid at the moment of eruption and was so rapidly cooled that there was no time for it to crystallize. When it solidified, the gasses dissolved in it were suddenly released, the whole mass immediately consolidated. Had it cooled under more pressure, it would have formed a solid glass, or obsidian. Any type of lava, if the conditions are favourable, may assume the pumiceous state, but basalt and andesite do not occur as often in this form as does rhyolite.

Small crystals of various minerals occur in many pumices; the most common are feldspar, pyroxene, amphibole, and zircon. The cavities (vesicles) of pumice are sometimes rounded and may also be elongated or tubular, depending on the flow of the solidifying lava. The glass itself forms threads, fibres, and thin partitions between the vesicles. Rhyolite aumices are white, andesite pumices often yellow or brown, and pumiceous basalts (such as occur in the Hawaiian Islands) pitch black.

Pumices are most abundant and most typically developed from silica-rich magmas; accordingly, they commonly accompany obsidian. In minute fragments, it has an exceedingly wide distribution over the Earth's surface. It occurs in all the deposits that cover the floor of the deepest portion of the oceans and is especially abundant in the abyssal red clay. Much of this pumice has been derived from submarine volcanic eruptions, but its presence is also accounted for by the fact that it will float on water for months and is thus distributed over the sea by winds and currents. After a time it becomes waterlogged and sinks to the bottom, where it gradually disintegrates and is incorporated in the muds and oozes of the ocean floor.

Fragmental texture. Rock fragments and glass shards embedded in a fine-grained (ash) matrix.

Texture - Fragmental

Step 2

The identification of fragmental-textured rocks can be quite complex. We have reduced the complexity for you, there is only one! Fragmental rocks get their name because they have rock fragments embedded in them . Do you see any, they should be obvious? The matrix material is usually volcanic ash that can feel gritty and sometimes contains small shards of glass. The rock can be light in weight. If your sample does not match this description, Go Back to the previous step.

Rock fragments in an ash/glass matrix,light weight and light colored :

Texture - Fragmental

Light colored	Broken rock fragments in a fine-grained, soft, ash matrix. Glass shards may be present.	

Your Rock is Volcanic Tuff!

VOLCANIC TUFF

Tuff is a termed used to describe a relatively soft, porous rock that is usually formed by the compaction and cementation of volcanic ash or dust. Tuffs may be grouped as vitric, crystal, or lithic when they are composed principally of glass, crystal chips, or the debris of pre-existing rocks, respectively. Some of the world's largest deposits of vitric tuff are produced by eruptions through a large number of narrow fissures rather than from volcanic cones.

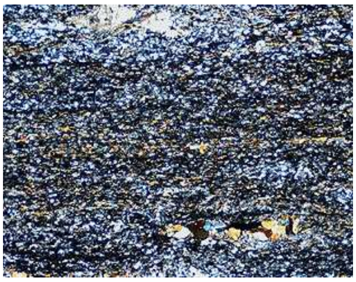
In extensive deposits, tuff may vary greatly not only in texture but also in chemical and mineralogical composition. There has probably been no geological period entirely free from volcanic eruptions; tuffs therefore range in age from Precambrian to Recent. Most of the older ones have lost all original textures and are thoroughly recrystallized. In some eruptions, foaming magma wells to the surface as hot gases and incandescent particles;

the shredded pumaceous material spreads swiftly, even over gentle gradients, as a glowing avalanche (nu馥 ardente) that may move many miles at speeds greater than 100 miles per hour. After coming to rest, the ejecta (erupted matter) may be firmly compacted by adhesion of the hot glass fragments to form streaky, welded tuffs (ignimbrites) such as those covering vast areas in Yellowstone National Park in the United States and the Owens Valley, CA (Bihop Tuff).

Metamorphic Rock Identification

The term metamorphism means to change. Most of us think of the metamorphosis that occurs when a caterpillar becomes a butterfly. While not as dramatic, similar changes can occur in rocks. Rocks will alter their form and appearance to suit new conditions Unfortunately, metamorphism is a slow process that occurs deep within the Earth. We cannot directly observe the process, but we can see the end result, metamorphic rocks.

METAMORPHIC ROCKS



Metamorphic rocks result from mineralogical and structural adjustments of solid rocks to physical and chemical conditions differing from those under which the rocks originally formed. Changes produced by surface conditions such as compaction are usually excluded. The most important agents of metamorphism are temperature, and pressure. Equally as significant are changes in chemical environment that result in chemical recrystallization where a mineral assemblage becomes out of equilibrium due to temperature and pressure changes and a new mineral assemblage forms.

Three types of metamorphism may occur depending on the relative effect of mechanical and chemical changes. Dynamic metamorphism, or cataclasis, results mainly from mechanical deformation with little long-term temperature change. Textures produced by such adjustments range from breccias composed of angular, shattered rock fragments to very fine-grained, granulated or powdered rocks with obvious foliation and lineation termed mylonites. Contact metamorphism occurs primarily as a consequence of increases in temperature where differential stress is minor. A common phenomenon is the effect produced adjacent to igneous intrusions where several metamorphic zones represented by changing mineral assemblages reflect the temperature gradient from the high-temperature intrusion to the low-temperature host rocks; these zones are concentric to the intrusion. Because the volume affected is small, the pressure is near constant. Resulting rocks have equidimensional grains because of a lack of stress and are usually fine-grained due to the short duration of metamorphism. Regional metamorphism results from the general increase of temperature and pressure over a large area. Grades or intensities of metamorphism are represented by different mineral assemblages. Regional metamorphism can be subdivided into different pressure-temperature conditions based on observed sequences of mineral assemblages. It may include an extreme condition, where partial melting occurs, called anatexis.

Other types of metamorphism can occur. They are retrograde metamorphism, the response of mineral assemblages to decreasing temperature and pressure; metasomatism, the metamorphism that includes the addition or subtraction of components from the original assemblage; poly-metamorphism, the effect of more than one metamorphic event; and hydrothermal metamorphism, the changes that occur in the presence of water at high temperature and pressure which affect the resulting mineralogy and rate of reaction.

TYPES OF METAMORPHISM

To more fully understand metamorphic rocks and metamorphic processes is necessary to briefly discuss the various types of metamorphism. This may seem like a simple task, but unfortunately, there is no general agreement among scientists upon how many different types of metamorphism occur in nature. For our purposes we will discuss only the three most common and leave the controversy to others! To go to a discussion of each type follow them below.

- Contact Metamorphism
- Regional Metamorphism
- Dynamic (cataclastic) Metamorphism

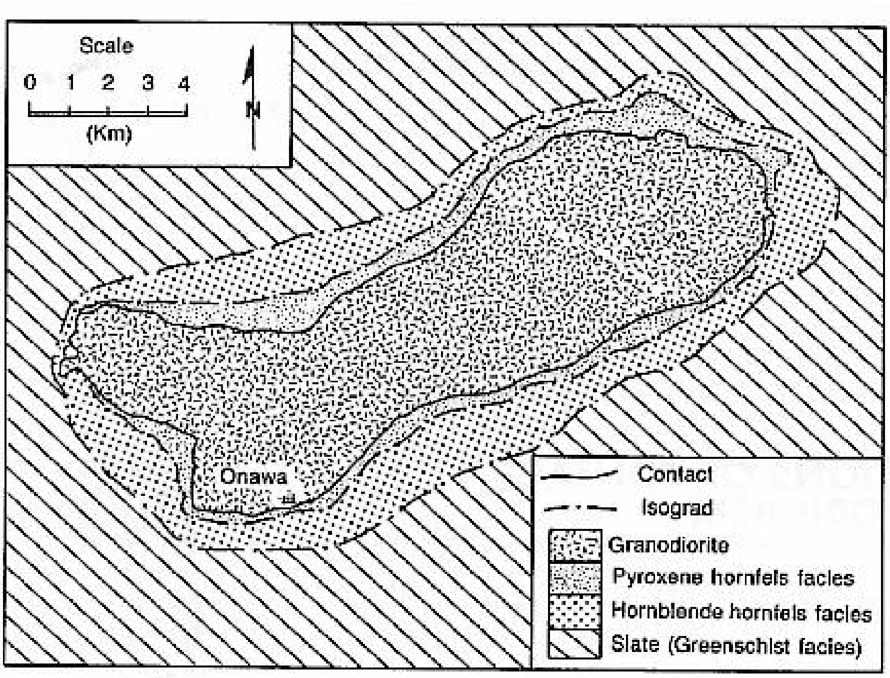
Contact Metamorphism

Contact metamorphism occurs locally, at and near the contacts between intrusions and the surrounding country or host rock. The heat introduced by the intrusion controls the metamorphism. The effects of increased temperature are most pronounced where intrusions occur at shallow levels. There, contrasts in temperature between country rock and intrusion are at a maximum. The fluid phase is also an important agent of contact metamorphism. It transports heat and has a profound influence on the chemistry and mineral composition of the rocks with which it comes in contact. Fluids are particularly important in the metamorphism of carbonate rocks. Contact metamorphism commonly produces fine-grained rocks termed *hornfels*. In addition to a variety of common minerals, such as quartz, feldspars, and epidote, hornfels locally contain unique phases. Typically, contact metamorphism occurs at shallower levels of the crust, where the pressure is relatively low (< 4 kb). At those shallow levels, the stresses characteristic of orogenic belts are generally absent and contact metamorphic rocks lack foliation.

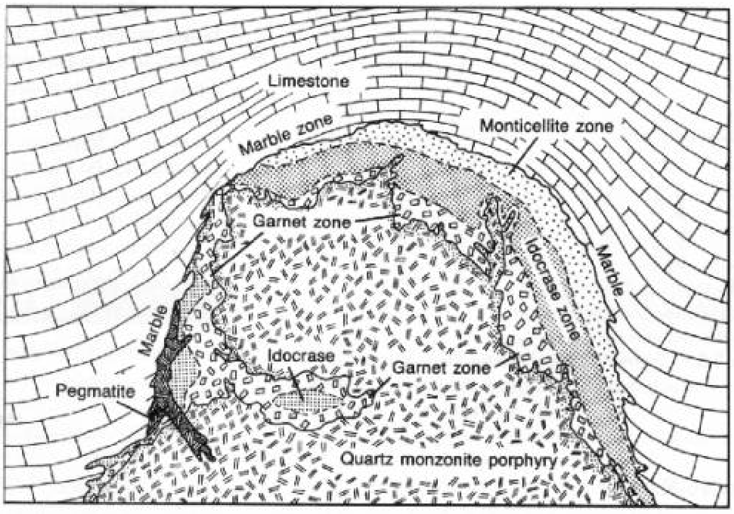
Contact Metamorphic Facies Series

Contact metamorphic rocks are found in *aureoles*, zones of metamorphic rock surrounding and associated with plutons. Observation of the occurrences of contact metamorphic rocks reveals that Zeolite, Prehnite-Pumpellyite, Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite facies constitute the *Contact Metamorphic Facies* Series.

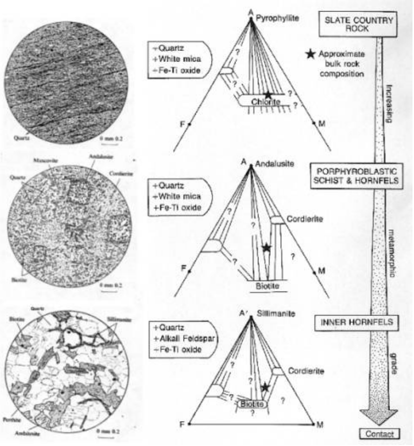
Minerals indicative of these facies include analcite, stilbite, wairakite, pyrophyllite, cordierite, andalusite, sillimanite, K-feldspar, orthopyroxene, sanidine, and mullite. In mafic/ultramafic rocks, albite, actinolite, epidote, hornblende, pyroxenes and olivine my occur . In carbonate rocks, minerals such as talc, tremolite, diopside, forsterite, grossularite, wollastonite, and spurrite may develop.



A classic example of a partial Contact Facies Series is provided by the contact aureole of the Devonian Onawa pluton of Maine (see figure to right). The granitic pluton was intruded into slate country rock previously metamorphosed under regional metamorphic conditions. The country rocks contain the assemblage Fe-Ti oxide + white mica + chlorite + quartz (figure below). The first evidence of contact metamorphism is the appearance of spots in the slates as far as 2 km from the pluton margin. The spots are cordierite porphyroblasts (largely replaced by phyllosilicates) and are part of the assemblage biotite + andalusite + cordierite + white mica + quartz + albite (figure). This assemblage is representative of the Hornblende Hornfels Facies.



This outer zone surrounds an inner zone, adjacent to the pluton, composed of the assemblage biotite + sillimanite + cordierite + alkali feldspar + quartz (figure). This assemblage is indicative the Pyroxene Hornfels Facies.



Conditions

The conditions of contact metamorphism are those of low to moderate pressure and low to high temperature. Pressures are generally less than 4 kilobars. Temperatures of metamorphism vary widely from 400-1000°C. Among the controlling factors are:

1. the temperature of the magma,
2. the temperature of the country rock at the time of intrusion,
3. the conductivities of the solidifying magma and the country rock,
4. the diffusivity (of both the country rock and the intrusion),
5. the heat of crystallization of the magma,
6. the heat capacity (the rate of change in the energy of reaction with change in temperature),
7. fluid transport, the heating or cooling by influx of water,
8. contributions from other sources, such as radioactive.

Now let's consider the metamorphic aureole at Crestmore, California (figure to the left). Quartz diorite and quartz monzonite have intruded a relatively pure limestone. The igneous rocks are surrounded by an aureole of variable width (< 3 cm-> 15 m) consisting of four parts. The outermost zone, referred to as the *marble* zone, consists of calcite marble and brucite-calcite marble. The marble zone is succeeded inwardly by the *monticellite zone,* consisting of rocks composed of calcite and monticellite in association with one or more of the various minerals clinohumite, forsterite, melilite, spurrite, tilleyite, and merwinite. An *idocrase zone* occurs interior to the monticellite zone. The idocrase zone contains rocks composed of idocrase in association with such minerals as calcite, diopside, wollastonite, phlogopite, monticellite, and xanthophyllite. Closest to the intrusion is the *garnet zone*, where diopside-wollastonite-grossularite rocks, containing minor calcite and quartz, occur.

Examination of the key minerals indicates that metasomatism has occurred. The progressive sequence of key minerals and their chemistries is as follows:

calcite	$CaCO_3$
calcite + brucite	$CaCO_3 + Mg(OH)_2$
monticellite	$CaMgSiO_4$
idocrase	$Ca_{10}Mg_2Al_4Si_9O_{34}(OH)_4$
grossularite - wollastonite - diopside	$Ca_3Al_2Si_3O_{12}$ - $CaSiO_3$- $CaMgSi_2O_6$

Notice that there is a progressive increase in the ratio Si/Ca towards the contact with the intrusive and a similar increase in Al. Chemical analyses of the rocks confirm these trends and also indicate a slight enrichment in Fe^{3+}. As the original rock was a Mg-bearing limestone, the first two assemblages shown in the table indicate isochemical (no change in the chemistry) metamorphism. The latter three suggest an introduction of silica and alumina, or metasomatism.

Regional Metamorphism

Mountain systems typically contain large belts of regionally metamorphosed rock. These are often foliated metamorphic rocks developed under medium to high temperatures. They occur in belts of regional extent, from which the term regional metamorphism was originally derived. The accompanying pressures vary from low to high. Geothermal gradients, which are likewise moderate to high, produce Buchan and Barrovian Facies series. Because the pressures of Buchan and Barrovian Facies series are commonly higher than are those of Contact Facies Series, they may contain different sequences of minerals.

- Buchan Facies Series forms under pressures, which, in the middle grades of metamorphism, are *lower* than that of the aluminum silicate triple point.

Consequently, the critical sequence of aluminum silicates is kaolinite -->pyrophyllite -->andalusite --> sillimanite.

- Barrovian Facies Series, in contrast, develops where pressures in the middle grades of metamorphism are *higher* than that of the aluminum silicate triple point. The resulting aluminum silicate mineral sequence is kaolinite -->pyrophyllite -->kyanite --> sillimanite.

The presence of either andalusite or kyanite on metamorphosed shales and siltstones at the middle grades of metamorphism is one feature that distinguishes these facies series from one another.

BUCHAN FACIES SERIES

The Buchan Facies Series takes its name from a region in the Scottish Highlands. In general, the geothermal gradients that give rise to the low pressures and high temperatures of Buchan Facies Series may be attributed to (a) regional heating from intrusion of groups of plutons at shallow to moderate depths; (b) plate collisions at convergent margins; and (3) crustal thinning. Buchan metamorphism is common, and a number of Buchan belts have been described from various parts of the world, notably Spain and Japan. Other localities include Maine, New Hampshire, Colorado, Oregon, Alaska, Australia, India, and Ireland.

The low-grade assemblages are virtually identical to those of the Barrovian Facies Series described below. Similarly, Greenschist Facies rocks are mineralogically similar to their equivalents in Barrovian Facies Series. It is in the Amphibolite Facies, where andalusite and cordierite appear, that the Buchan Facies Series is distinguished from the higher-pressure Barrovian rocks.

The various phase assemblages developed in each metamorphic zone of the Buchan Facies Series indicate various reactions. In pelitic (shale) rocks, at the lowest grade, the Zeolite Facies contains assemblages such as

kaolinite-illite-smectite-chlorite-quartz-analcite-K feldspar

At slightly higher-grade conditions, where assemblages of the Zeolite Facies are replaced by those of the Prehnite-Pumpellyite Facies, some minerals, such as K feldspar, are absent from many rocks, and new phases appear, such as white mica, prehnite, pumpellyite and albite. Smectites and K feldspar are among the first minerals that may disappear from aluminous rocks. Kaolinite also commonly disappears from pelitic assemblages during development of Prehnite-Pumpellyite Facies assemblages.

Typical assemblages in Greenschist Facies pelitic rocks include

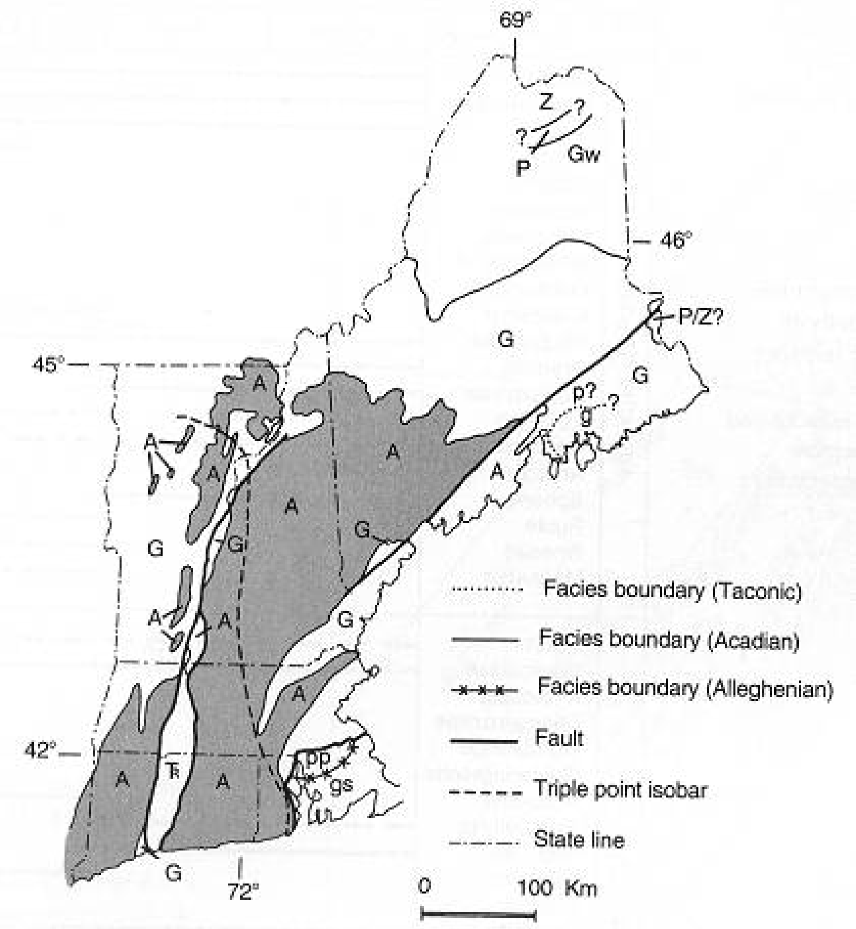
white mica-chlorite-quartz-albite-magnetite-epidote-pyrophyllite-biotite-garnet-ilmenite

The Greenschist-Amphibolite Facies boundary is a broad zone. The disappearance of albite marks the maximum upper limit of the Greenschist Facies. Both albite and pyrophyllite are absent from Amphibolite Facies rocks, whereas cordierite and the aluminum silicates andalusite (at lower grades) and sillimanite (at higher grades) characterize aluminous bulk compositions. Additional phases that may occur in pelitic rocks include, but are not restricted to, chloritoid, alkali feldspar, tourmaline, apatite, and sphene. Reactions distinctive of Buchan Facies Series are those defining the appearance of andalusite and cordierite, which combined with the disappearance of albite, mark the transition to the Amphibolite Facies.

Pelitic rocks in the Granulite Facies are distinguished by the general absence of white mica, by the presence of alkali feldspar + sillimanite or orthopyroxene, and by the occurrence of the assemblage cordierite + orthopyroxene.

Example: Buchan Metamorphism, Northern New England, U.S.A.

Perhaps the best-known Buchan Facies Series is that of northern New England. A line representing the aluminum silicate triple point extends through New England-from Rhode Island, through central Massachusetts, across western New Hampshire, and into northeastern Vermont-marking a change from a Barrovian Facies Series on the southwest to a Buchan Facies Series on the northeast (figure).



In the Buchan Facies Series of northeastern New England isograds have been mapped in the widely distributed pelitic rocks, including biotite, garnet, andalusite-staurolite, cordierite-staurolite, sillimanite, and K feldspar-sillimanite (Greenschist Facies). Locally, muscovite coexists with sillimanite and K feldspar in pelitic rocks of the uppermost zone; thus, the rocks containing these minerals belong to the Amphibolite Facies. Granulite Facies rocks are present only to the south, in New Hampshire, Massachusetts, and northern Connecticut. In northernmost Maine, Quebec, and New Brunswick, the Zeolite and Prehnite-Pumpellyite Facies are represented by analcite, prehnite-pumpellyite, and pumpellyite-epidote-actinolite zones in metaclastic and metavolcanic rocks.

Differences and Similarities Between Contact and Buchan Facies Series

	Contact	**Buchan**
Distribution	local	regional
Foliation	non-foliated	foliated
Hi Grade Facies	Sanidinite	Granulite
Location	near pluton	orogenic belt

BARROVIAN FACIES SERIES

The Barrovian Facies Series occurs in a number of Paleozoic mountain belts, as well as in some of Precambrian age. Notable are the Caledonides of northwestern Europe, including the classic region in the Scottish Highlands, and parts of the Appalachian Mountain System of eastern North America. Other belts with Barrovian rocks occur in Idaho, Colorado, British Columbia, Alaska, Venezuela, Spain, southern Europe and Asia and Japan. Precambrian belts of Barrovian rocks occur in the Black Hills of South Dakota, the Rocky Mountains, and Labrador, Quebec, and Ontario (Canada).

The Paleozoic orogenic belts are clearly associated with convergent plate margins. Both Barrovian and Buchan Facies series develop at such margins. In convergent zones, regional heating due to the rise of plutons into the overlying plate (the plate above the subduction zone) is the general cause of metamorphism, but migrating fluids may also transport heat.

The zones of metamorphism in the Scottish Highlands originally described by Barrow (1893) include six distinct mineral assemblages that occur in the rock types listed below:

Chlorite Zone (slates, phyllites, and schists)

quartz-albite-white mica-chlorite-microcline ± calcite

Biotite Zone (phyllites and schists)

quartz-albite-white mica-chlorite-biotite ± microcline ±calcite ± epidote

Almandine (Garnet) Zone (phyllites and schists)

quartz-albite-white mica-biotite-garnet ± chlorite

Staurolite Zone (schists)

quartz-oligoclase-white mica-biotite-garnet-staurolite

Kyanite Zone (schists)

quartz-oligoclase-white mica-biotite-garnet-kyanite ±staurolite

Sillimanite Zone (schists and gneisses)

quartz-oligoclase-biotite-sillimanite ± kyanite ± K-feldspar ± white mica

At the lowest grade, in the Zeolite Facies, which forms under conditions just above those of diagenesis, assemblages are characterized by clay minerals. Assemblages may include

kaolinite-illite-smectite-chlorite-quartz-analcite

At slightly higher-grade conditions, assemblages of the Zeolite Facies are replaced by those of the Prehnite-Pumpellyite Facies. New phases appear, including albite, white mica and stilpnomelane. As was the case in Buchan Facies Series, K feldspar and smectites are among the first minerals to disappear from aluminous rocks. Kaolinite also is commonly absent from Prehnite-Pumpellyite Facies rocks.

As the P-T conditions increase, Greenschist Facies assemblages with new minerals form. Typical assemblages in pelitic rocks include

white mica-chlorite-chloritoid-quartz-albite-magnetite-biotite-epidote-garnet-pyrophyllite

As is the case in the Buchan Facies Series, the Greenschist-Amphibolite Facies boundary is a broad zone. The disappearance of albite marks the maximum upper limit of the Greenschist Facies. Thus, albite, like pyrophyllite, is absent from Amphibolite Facies rocks. Staurolite, rather than chloritoid, occurs in the lower part of the Amphibolite Facies and the aluminum silicates kyanite (at lower grades) and sillimanite (at higher grades) characterize aluminous bulk compositions. Typical assemblages include

white mica-chlorite-biotite-quartz-plagioclase-garnet-magnetite-staurolite-ilmenite-kyanite-sillimanite

The Granulite Facies is distinguished by the general absence of white mica and the presence of orthopyroxene and cordierite. Pelitic assemblages include

biotite-garnet-sillimanite-K feldspar-andesine-quartz-cordierite-orthopyroxene-sillimanite-zircon

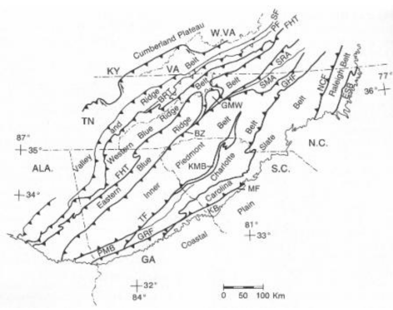
The quartzo-felspathic rocks differ from the pelitic rocks. Quartz and feldspar are the dominant phases, rather than the phyllosilicates, and calcium-bearing phases are common. Additional minerals that may occur include stilbite, calcite, stilpnomelane, actinolite and hornblende.

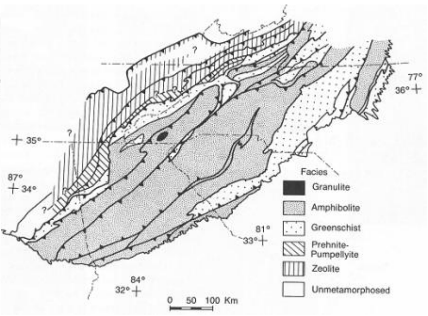
Example: Barrovian Metamorphism in the Southern Appalachian Orogen

The southern Appalachian Orogen extends from central Virginia to Alabama. It is a complex orogenic belt, parts of which have experienced regional metamorphism during four orogenic events. The ages of these events are Proterozoic, Ordovician (the Taconic Orogeny), Devonian-Mississippian (the Acadian Orogeny), and Pennsylvanian-Permian (the Alleghanian/Appalachian Orogeny).

While the Southern Appalachian Orogen is one of the major regions of Barrovian Facies Series rocks in North America, analysis of the metamorphism there has been confounded by several factors. First, the various tectonic belts (terranes) in the southern Appalachian Orogen have been juxtaposed by significant movements of various types along major faults—in several cases, *after* metamorphism had occurred. This problem is particularly significant in the central and eastern parts of the Orogen. Second, the thermal significance of various metamorphic zones is open to question.

A map of the orogen, showing the approximate positions of metamorphic facies of Paleozoic age, is presented below. A broad range of rock types exists in the region, but carbonate rocks, especially impure carbonate rocks, are relatively rare in the higher-grade parts of the metamorphic belt, whereas mafic and ultramafic rocks are rare to nonexistent in the low-grade zones. Rocks of the Zeolite and Prehnite-Pumpellyite Facies occur primarily in the Valley and Ridge Belt. At these lowest grades of metamorphism, the pelites are characterized by clays and the carbonate rocks by calcite and/or dolomite ± quartz. Greenschist Facies assemblages are distributed in the western Blue Ridge Belt. Rocks of this grade consist of younger (Cambrian) sedimentary and igneous rocks and older (Proterozoic) polymetamorphic rocks. Quartz-rich metaclastic rocks typically contain the assemblage quartz-white mica-chlorite-alkali feldspar. Quartz-feldspar gneisses, probably products of retrograde metamorphism of Precambrian Amphibolite and Granulite facies rocks, contain similar assemblages. Pelitic rocks are composed of the assemblage chlorite-white mica-quartz-albite. In higher-grade assemblages, garnet is present. Metabasites contain assemblages such as chlorite-epidote- albite-quartz-actinolite.





Much of the eastern Blue Ridge Belt is composed of rocks of the Amphibolite Facies. Migmatites are common. Pelitic mica schists consist of various assemblages containing staurolite, kyanite, and sillimanite. Quartzo-feldpathic rocks are composed predominantly of

the assemblage plagioclase-quartz-biotite-white mica-garnet. Mafic rocks are typical amphibole schists and gneisses, with hornblende and plagioclase as the dominant phases. Geothermometry and geobarometry indicate that the Amphibolite Facies rocks of the Blue Ridge were metamorphosed at temperatures between 500 and 850 °C at pressures of 5-11 kb.

Paleozoic Granulite Facies rocks have been recognized at only a few localities. Aluminous schist consists of biotite-garnet-sillimanite-K feldspar-andesine-quartz. Quartzo-feldpathic rocks contain assemblages such as andesine-quartz-K feldspar-biotite-garnet. A typical metabasite assemblage is hornblende-bytownite-biotite-orthopyroxene. Given that the estimated P-T conditions do not differ significantly from those for Amphibolite Facies metamorphism, the zones of Granulite Facies metamorphism probably represent local areas in which the rocks were dehydrated by previous metamorphic events.

Because the overall metamorphic pattern in the Southern Appalachian orogen developed over a long period of time, it is difficult to discern the *complete* patterns of metamorphism *associated with each orogenic event.* In the western part of the orogen, that problem is increased where thrust faults have shortened the width of the orogen, concealing sections of the metamorphic belt. Nevertheless, the elongate metamorphic zones are typical of orogenic Barrovian Facies Series metamorphic belts.

BLUESCHIST FACIES SERIES

Glaucophane imparts an attractive blue hue to rocks. This feature undoubtedly accounts for the considerable interest given to the relatively uncommon glaucophane schists (the "blueschists") of the California Coastal Ranges. The blue color also serves as the basis for the name Blueschist Facies, even though this facies contains large volumes of rock that are neither blue nor schistose. It is also true that all rocks containing blue amphibole do not belong to the Blueschist Facies.

The Blueschist Facies develops in terranes in which the geothermal gradient is low or the overall P/T is moderate to high. Two sub-types of facies series are recognized in such terranes: the Sanbagawa Facies Series and the Franciscan Facies Series. In the Sanbagawa Facies Series, the maximum temperatures are somewhat higher than in the Franciscan Facies Series. The facies sequence is Zeolite--Prehnite-Pumpellyite--Blueschist --Greenschist--Amphibolite. In the Franciscan Facies Series, the facies sequence is Zeolite--PrehnitePumpellyite--Blueschist--Eclogite.

Bluescist Facies series are widely distributed. They occur in North, Central, and South America, in the Caribbean region, in Europe, especially in the Alps, in the Middle East, in Asia, and in the circum-Pacific region (figure). Typically, these facies series form on the outer (trench) side of a paired metamorphic belt associated with a subduction zone. In some cases, high P/T (low-temperature) rocks form where subduction-induced collision between a continent and island arc or another continent is inferred.

Young mountain belts contain the majority of these rocks, but early Paleozoic and rare Precambrian Blueschist Facies rocks are known. The two sub-facies series of high P/T metamorphism take their names from well-studied examples on opposite sides of the Pacific Ocean. The Franciscan Facies Series is named for the Franciscan Complex of western California and southern Oregon. The Sanbagawa Facies Series takes its name from rocks exposed in southeastern Japan.

Mineral assemblages, facies, and textures set the high P/T facies series apart from those of lower P/T. Minerals such as lawsonite occur only at high P and low T. In general, the rocks in outer metamorphic belts are metamorphosed pieces of ocean crust and overlying sediments. The most common of the critical minerals that appear include laumontite, pumpellyite, glaucophane, lawsonite, aragonite, jadeitic pyroxene, and omphacite.

In the Zeolite Facies, common mineral assemblages are

heulandite-quartz-analcite-vermiculite-white mica-laumontite-calcite

These are replaced in the Prehnite-Pumpellyite Facies by assemblages such as

quartz-albite-prehnite-pumpellyite-white mica-chlorite- stilpnomelane-calcite

Blueschist Facies assemblages include

quartz-albite-lawsonite-pumpellyite-chlorite-white mica-jadeitic pyroxene-glaucophane-aragonite

Rare Eclogite Facies rocks contain

quartz-white mica-omphacite-glaucophane-garnat-epidote

Petrogenetic Models

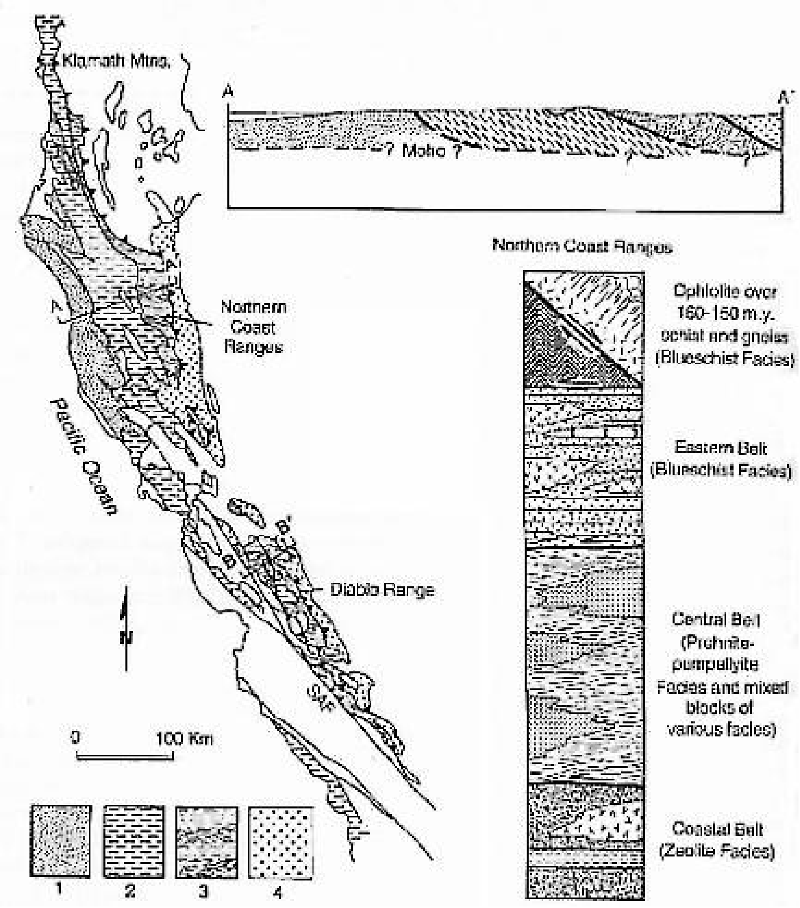
Three hypotheses for the origin of Blueschist Facies Series rocks are advocated by various geologists.

- *Metasomatic Recrystallization Hypotheses* - Blueschists result from low-pressure metasomatism induced by concentrated, saline pore fluids evolved during serpentinization.
- *Tectonic Overpressure Model* - This hypothesis argues that tectonic overpressures cause Blueschist Facies Series metamorphism. Tectonic overpressures develop below a regional thrust fault that is capped by serpentinite. Trapped water creates the overpressures.
- *Burial Metamorphism Hypothesis* - Deep burial may result from either sedimentation or tectonic thickening of the crust via faulting. The tectonic setting of high P/T

metamorphic belts is consistent with this hypothesis. In particular, the presence of Blueschist Facies Series rocks in paired metamorphic belts suggests that subduction and associated accretion of subducted rocks, are generally responsible for Blueschist Facies and related rocks.

Example: Regional Hign P/T Metamorphism of the Franciscan Complex, CA

The Franciscan Complex forms the structurally complicated basement of much of the California Coast Ranges. It is composed of a wide variety of rock types, not all of which are metamorphosed. As a group, however, metamorphic rocks dominate. Graywacke and metagraywacke and associated shale and metashale are the most abundant rock types. Chert, pillow basalt, limestone, conglomerate, ultramafic rocks and the metamorphic equivalents of all of these also occur at numerous localities. Well known among the metamorphic rocks are eclogites, glaucophane schists and gneisses, and actinolite and hornblende schist and gneiss that occur in isolated blocks and sheets. The isolated masses most commonly occur in melanges. In addition, Eclogite, Blueschist, Amphibolite, and rare Greenschist Facies rocks form slabs and tectonic blocks along faults.



In the northern Coast Ranges, rocks of six metamorphic facies are distributed across three major, fault-bounded belts that are successively younger from east to west. High-grade schists and gneisses, in tectonic blocks and slabs, form a fourth unit that locally caps the Franciscan Complex along its eastern edge. Each belt is subdivided into several thrust sheets or fault blocks (commonly designated as terranes) that include various formations, broken formations, dismembered formations, and melanges. The Central Belt is largely melange. In contrast, the adjoining Eastern and Coastal belts, though locally containing melange, consist predominantly of rock bodies with greater internal coherence. In the area at the southern end of the Northern Coast Ranges, in the San Francisco Bay area and to the north for several tens of kilometers, the structural and metamorphic patterns are highly disrupted by Cenozoic faulting. The metamorphic patterns of the northern Coast Ranges are more regular than the patterns in the south.

In the north, the westernmost belt, the Coastal Belt, is a metawacke and metashale-dominated, *Zeolite Facies* metamorphic belt. The metawackes contain laumontite, prehnite, or pumpellyite. The Central Belt melanges structurally overlie the Coastal Belt rocks. Most rocks of the Belt are considered to belong to the *Prehnite-Pumpellyite Facies.* However, because the Central Belt consists primarily of an assemblage of melanges, rocks from Zeolite Facies to Eclogite and Amphibolite Facies are present. To the east and structurally overlying the Central Belt is a faulted *Bluesehist Facies* belt dominated by metasedimentary rocks and containing a variety of pumpellyite, lawsonite, and jadeitic-pyroxene-bearing assemblages.

Analyses of the conditions that produced the metamorphic rocks in the Franciscan Complex suggest metamorphism of Eastern Belt rocks occurred at P=6-10kb and T= 125-350 °C, whereas Central Belt melange metamorphism resulted from pressures of 2-6kb and temperatures of 125-300 °C. Zeolite Facies metamorphism of Coastal Belt rocks occurred at about P= 1-3kb and T=100-200 °C

Dynamic Metamorphism

Dynamic (cataclastic) metamorphism is metamorphism of rock masses caused primarily by stresses that yield relatively high strain (deformation) rates. More simply, it is metamorphism resulting from deformation. The deformation may be dominantly brittle, in which case rock and mineral grains are broken and crushed, or it may be dominantly ductile, in which case plastic behavior and flow occur via structural changes within and between grains.' Temperatures during dynamic metamorphism are typically elevated and may be caused by the deformation process. Fluids commonly contribute to the metamorphic process, both by altering chemistry and by aiding recrystallization.

Both local and regional dynamic metamorphism are recognized. At the local scale, in narrow zones from less than 1 cm to several meters wide, brittle or ductile deformation along faults and fold limbs causes rock to break, recrystallize, and even to melt. Similarly, both brittle and ductile deformation, as well as melting, occur during impacts of extraterrestrial bodies. Brittle and ductile deformation processes also operate at the regional scale.

The rocks produced at all scales by dynamic metamorphism are rocks composed of fragments of preexisting material (porphyroclasts), surrounded by a deformed matrix, the texture or mineral composition of which was produced by metamorphic processes. Such rocks, which fit into the broad category of clastic rocks, referred to as dynamoblastic rocks.

Occurrences of Dynoblastic Rocks

Faults are common within the crust of the Earth. Since faults are deformation zones, dynamoblastic rocks associated with faults are a common feature. In addition, folds and related deformation zones are relatively common in the roots of mountain belts. Even in zones in which newly formed rocks are only partially lithified, for example, in soft sediments on the seafloor, deformation may yield dynamically metamorphosed rocks. Particularly noteworthy among the local- to regional-scale zones of dynamoblastic rock are the mylonite zones associated with metamorphic core complexes and the melanges of outer metamorphic belts. Melanges are, in fact, mappable masses of dynamoblastic rock of local to regional dimensions. Impact structures with dynamoblasric rocks include Meteor Crater in Arizona and the Ries Basin of Germany.

Regional zones of dynamoblastic rocks occur at plate boundaries. Along spreading ridges, regional stress may be widespread enough to yield dynamically metamorphosed zones of rock. Perhaps more commonly, ductile deformation is concentrated in narrow zones within a regional terrane of schistose ultramafic rocks. Most local and regional zones of this type are probably subducted and are not preserved. Nevertheless, evidence of their existence is preserved locally in mantle slabs of accreted ophiolites. More commonly, oceanic crustal rocks are deformed along transform faults. Examples of rocks deformed in this way are exposed in the Sierra Nevada of California, in northern Italy, and on the island of Cyprus. Exposures of transform faults that transect the continents also reveal brittly and ductily deformed rocks, such as those along the San Andreas Fault System in California.

The most extensive development of dynamically metamorphosed rocks occurs in the mountain belts. Rocks of the transform fault zones may be accreted here, but most commonly, the regional zones of dynamoblastic rock are produced by deformation associated with the plate (and continent) collisions that yield the mountain range. At the shallower and cooler levels of orogens, *melanges*, formed by brittle deformation, ductile deformation, or both, are widespread. Well known examples include the melanges of the Franciscan Complex of California, and the Apennine Mountains of Italy."

Ductile deformation zones of regional extent are also common in the internal, high-temperature zones of the orogenic belts. Here, discrete fault lines are replaced by extensive zones of recrystallization and flow. Examples of such ductile deformation zones include some of the more regionally extensive mylonitic zones associated with metamorphic core complexes in the Rocky Mountain region, the Brevard Zone of the Southern Appalachian

Orogen, faults in the Grenville Tectonic Zone in Ontario and the Moine Thrust of the Scottish Highlands.

TEXTURE AND CLASSIFICATION

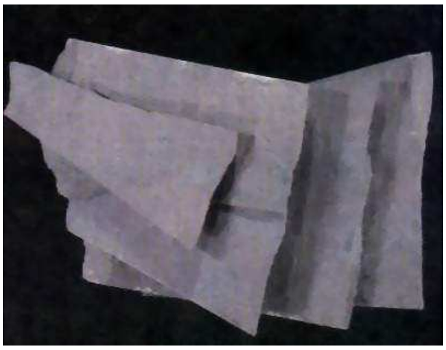
In order to classify metamorphic rocks, it is also necessary to take of the subjects of texture and classification schemes. If you have completed the igneous rock exercise you might note that these discussion topics are similar with one exception. We also discussed the Minerals of Igneous Rocks, there is no such discussion of metamorphic minerals. This does not mean mineralogy of metamorphic rocks is not an important topic, rather the number of metamorphic minerals is too large to discuss in an introductory exercise. Fortunately, it is necessary to recognize only a few common minerals to name most metamorphic rocks. You have seen these minerals if you completed the minerals exercise and in some cases again in igneous rocks.

- Metamorphic Rock Textures
- Classification of Metamorphic Rocks

METAMORPHIC ROCK TEXTURES

Foliated Texture

The mineral constituents of foliated metamorphic rocks are oriented in a parallel or suhparallel arrangement. Foliated metamorphic rocks are generally associated with regional metamorphism. Four kinds of foliated textures arc recognized. In order of increasing metamorphic grade, these are *slaty*, *phyllitic*, *schistose* and *gneissic.*



Slaty Texture - This texture is caused by the parallel orientation of microscopic grains. The name for the rock with this texture is *slate* , and the rock is characterized by a tendency to separate along parallel planes. This feature is a property known as *slaty cleavage.* (Slaty cleavage or rock cleavage is not to be confused with cleavage in a mineral, which is related to the internal atomic structure of the mineral.)

Phyllitic Texture - This texture is formed by the parallel arrangement of platy minerals, usually micas, that are barely macroscopic (visible to the naked eye). The parallelism is often silky, or crenulated. The predominance of micaceous minerals imparts a sheen to the hand specimens. A rock with a phyllitic texture is called a *phyllite.*

Schistose Texture This is a foliated texture resulting from the suhparallel to parallel orientation of platy minerals such as chlorite or micas. Other common minerals present are quartz and amphiholes. A schistose texture lies between the parallel platy appearance of phyllite and the distinct banding of gneissic texture. The average grain size of the minerals is generally smaller than in a gneiss. A rock with schistose texture is called a *schist*

Gneissic Texture This is a coarsely foliated texture in which the minerals have been segregated into discontinuous hands, each of which is dominated by one or two minerals. These bands range in thickness from 1 mm to several centimeters. The individual mineral grains are macroscopic and impart a striped appearance to a hand specimen. Light-colored bands commonly contain quartz and feldspar. and the dark hands are commonly composed of hornblende and hiotite. Accessory minerals are common and are useful in applying specific names to these rocks. A rock with a gneissic texture is called a *gneiss.*

Nonfoliated Texture

Metamorphic rocks with no visible preferred orientation of mineral grains have a nonfoliated texture. Nonfoliated rocks commonly contain equidimensional grains of a single mineral such as quartz, calcite, or dolomite. Examples of such rocks are *quartzite* , formed from a quartz sandstone, and *marble* , formed from a limestone or dolomite. Conglomerate that has been metamorphosed may retain the original textural characteristics of the parent rock, including the outlines and colors of the larger grain sizes such as granules and pebbles. However, because metamorphism has caused recrystalliza tion of the matrix, the metamorphosed conglomerate is called *metaconglomerate.* In some cases, the metamorphism has deformed the shape of the gran ules or pebbles; in this case the rock is called a *stretched pebble conglomerate.*

Quartzite and metamorphosed conglomerate can be distinguished from their sedimentary equivalents by the fact that they break *across* the quartz grains, not around them. Marble has a crystalline appearance and generally has larger mineral grains than its sedimentary equivalent.

Examples of Nonfoliated Texture

A fine-grained (dense-textured), nonfoliated rock usually of contact metamorphic origin is *horniels.* Hornfels has a nondescript appearance because it is usually some medium to dark shade of gray, is lacking in any structural characteristics, and contains few if any recog nizable minerals in hand specimen.The metamorphic equivalent of bituminous coal is *anthracite coal.*

METAMORPHIC ROCK CLASSIFICATION

Classification

When preexisting rocks are exposed to conditions of high temperature and/or pressure they undergo solid-state changes (they "metamorphose") to become metamorphic rocks. The rock doesn't melt, but it changes state by one or both of these processes:

- mineral changes - growth of new minerals that are more stable under conditions of high temperature/pressure
- textural changes - recrystallization, alignment of platy minerals, usually as a result of unequal application of stress

The first thing to notice when you look at a metamorphic rock is its texture. Is the rock foliated or not? Foliation refers to flat or wavy planar features (looking like layers) caused by the alignment of platy minerals such as mica. Foliation may also look like alternating bands of light and dark minerals. In contrast, a nonfoliated rock has interlocking grains with no specific pattern. Foliated rocks (Table 1) are classified based on metamorphic grade: the lower the metamorphic grade, the smaller and finer the crystal size. Nonfoliated rocks (Table 2) are classified based on composition, and this usually depends on the type of rock it originally formed from (called the protolith).

TABLE 1: FOLIATED (banded) ROCK CLASSIFICATION

Metamorphic Environment	50-300°C	300-450°C	Above 450°C
Metamorphic Grade	Low	Intermediate	High
Rock Name	**SLATE**	**SCHIST**	**GNEISS**
Rock Description	Minerals not visible with the naked eye or with a hand lens, rock shows slaty cleavage, is usually dark-colored. A product of low-grade metamorphism of shale or mudstone.	Rock is medium to coarse grained with visible grains of mica or other metamorphic minerals. Often shiny due to reflection of mica on foliation planes. Product of intermediate grade metamorphism of	Rock is coarse grained and usually banded with alternating layers of light and dark minerals. Foliation bands may be folded. Product of high grade metamorphism of shale, schist, granite

		shale, slate, phyllite, basalt or granite.	or many other rock types.

TABLE 2. NONFOLIATED (not banded) ROCK CLASSIFICATION			
	MARBLE	**QUARTZITE**	**ANTHRACITE COAL**
Mineral(s)	calcite	quartz	crystalline carbon
Description	Coarse-grained recrystallized limestone or dolomite. Typically harder than the protolith. May have dark bands due to organic impurities.	Rock has intergrown quartz grains, thus is massive and hard. Protolith is sandstone. Intermediate to high grade metamorphism.	Hard, black shiny coal; product of low-grade metamorphism of bituminous coal.

Step 1

The first step involves determining the texture of your unknown rock sample. There are only two metamorphic rock textural types, foliated and nonfoliated. Examine your rock and CLICK on the appropriate texture to move to the next identification step.

Foliated texture. Sets of flat or wavy parallel planes that represent the preferred orientation of the minerals in the rock under a deforming pressure. The main cause of foliation is the presence of platy minerals which are easily elongated such as micas or amphibole.

Texture - Foliated

Step 2

The identification of foliated metamorphic involves an additional step. We must examine the foliated rock to see if the individual mineral grains are visible to the eye

GRAINS VISIBLE:

1- Coarse black and white banding: Feldspar, quartz, biotite and amphibole commom

Texture - Foliated
Grains Visible

Black and white banding	Quartz, feldspar, biotite and amphibole may be present	

Your Rock is Gneiss!

GNEISS

Gneiss has a distinct banding, which is apparent in hand specimen or on a microscopic scale. Gneiss usually is distinguished from schist by its foliation and schistosity; gneiss displays a well-developed foliation and a poorly developed schistosity and cleavage. It is convenient to think of a gneiss as a rock with parallel, somewhat irregular banding which has little tendency to split along planes. In contrast, schist typically is composed of platy minerals with a parallel geometric orientation that gives the rock a tendency to split along planes; banding is usually not present.

Gneiss is medium to coarse-grained and may contain abundant quartz and feldspar. The banding is usually due to the presence of differing proportions of minerals in the various bands; dark and light bands may alternate because of the separation of mafic and felsic minerals. Banding can also be caused by differing grain sizes of the same minerals. The mineralogy of a particular gneiss is a result of the complex interaction of original rock composition, pressure and temperature of metamorphism, and the addition or loss of components.

Gneiss can be classified on the basis of minerals that are present, process of formation, chemical composition, or probable parent material. Orthogneiss is formed by the metamorphism of igneous rocks; paragneiss results from the metamorphism of original sedimentary rocks. Augen gneiss contains stubby lenses of feldspar and quartz having the appearance of eyes scattered through the rock. In some areas, gneiss grades laterally into granitic rocks with the characteristics of typical igneous granite. This feature is one of the important factors that have led some to call upon a metamorphic process (granitization) for the development of granitic plutons.

Gneiss is the principal rock over extensive metamorphic terrains. The banding may be oriented nearly parallel to the Earth's surface or may have a steep dip. Such orientations can be interpreted in terms of the stresses that prevailed during the formation of the rock, but they also may be inherited from the rock that was metamorphosed.

2- Obvious foliation, a few large grains may be present, various colors: Muscovite, garnet, talc and chlorite commom

Texture - Foliated
Grains Visible

Obvious foliation, various colors	Muscovite, biotite chlorite, talc or garnet may be present	

Your Rock is Schist!

SCHIST

Schist is a medium crystalline rock that has a highly developed schistosity, or tendency to split into layers. Unlike its close cousin gneiss, banding is poorly developed or absent. Most schists are composed largely of platy minerals such as muscovite, chlorite, talc, biotite, and graphite; feldspar and quartz are much less abundant in schist than in gneiss. The green color of many schists and their formation under a certain range of temperature and pressure has led to a distinction of the greenschist facies in the mineral facies classification of metamorphic rocks. The parallel orientation of the platy minerals and well-developed folding of many schists indicate formation under stresses that are not the same in all directions. The mineralogy and high water content of the minerals indicate that they were formed under conditions of relatively low temperature and pressure.

Schists are usually classified on the basis of their mineralogy, with varietal names that indicate the characteristic mineral present. Talc schist contains abundant talc; it has a greasy feel, a well-developed schistosity, and a grayish-green colour. Mica schist often contains muscovite mica rather than biotite, although both minerals are common. It represents a somewhat higher grade of metamorphism than talc schist and is more coarse-grained; individual flakes of mica can be seen.

GRAINS NOT VISIBLE:

1- Silky sheen, fair rock cleavage, often gray: Muscovite or chlorite may be bearly discernable:

Texture - Foliated
Grains NOT Visible

Silky sheen, fair-poor rock cleavage, gray to green	Muscovite, biotite chlorite may be barely visible	

Your Rock is Phyllite!

PHYLLITE

Phyllite is a fine-grained metamorphic rock formed by the low grade metamorphism of fine-grained, sedimentary rocks, such as mudstones or shales. Phyllite has a marked fissility (a tendency to split into sheets or slabs) due to the parallel alignment of platy minerals; it may have a silky sheen on its surfaces due to tiny plates of micas. Its grain size is larger than that of slate but smaller than that of schist.

Phyllite is formed by relatively low-grade metamorphic conditions in the lower part of the greenschist facies. Parent rocks may be only partially metamorphosed so that the original mineralogy and sedimentary bedding are partially preserved. Depending upon the direction of the stresses applied during metamorphism, phyllite sheets may parallel or crosscut the original bedding; in some rocks, two stages of deformation, called precrystalline and postcrystalline deformations, can be distinguished on the basis of two orientations of definable surfaces in the rock. Precrystalline surfaces have slaty cleavage, or flow cleavage, whereas postcrystalline surfaces have fracture, or strain-slip cleavage. Such terms can be used only when the type of deformation and its relation to time can be determined.

2- Dull luster, excellent rock cleavage, various colors: No minerals visible:

Texture - Foliated
Grains NOT Visible

Dull luster, excellent rock cleavage, gray, red green or black	No visible minerals	

Your Rock is Slate!

SLATE

Slate is a very fine-grained, metamorphic rock that splits readily into thin slabs having great tensile strength and durability. A true slates does not, as a rule, split along the bedding plane but along planes of cleavage, which may intersect the bedding plane at high angles. Slate is formed under low-grade metamorphic conditions (low temperature and pressure). The original material was a fine clay, usually in the form of a sedimentary rock (e.g., a mudstone or shale). The parent rock may be only partially altered so that some of the original mineralogy and sedimentary bedding are preserved; the bedding of the sediment as originally laid down may be indicated by alternating bands, sometimes seen on the cleavage faces. Cleavage is an inherited structure, the result of pressure acting on the rock when it was deeply buried beneath the Earth's surface. The direction of cleavage depends upon the direction of the stresses applied during metamorphism.

Slate may be black, blue, purple, red, green, or gray. Dark slates usually owe their color to carbonaceous material or to finely divided iron sulfide. Reddish and purple varieties owe their color to the presence of hematite (iron oxide), and green varieties owe theirs to the presence of much chlorite, a green micaceous clay mineral. The principal minerals in slate are muscovite and biotite (in small, irregular scales), chlorite (in flakes), and quartz (in lens-shaped grains).

Slates are split from quarried blocks about 3 inches thick. A chisel, placed in position against the edge of the block, is lightly tapped with a mallet; a crack appears in the direction of cleavage, and slight leverage with the chisel serves to split the block into two pieces with smooth and even surfaces. This is repeated until the original block is converted into 16 or 18 pieces, which are afterward trimmed to size either by hand or by means of machine-driven rotating knives.

Slate is sometimes marketed as dimension slate and crushed slate. Dimension slate is used mainly for electrical panels, laboratory tabletops, roofing and flooring, and blackboards. Crushed slate is used on composition roofing, in aggregates, and as a filler. Principal production in the United States is from Pennsylvania and Vermont.

3- Shiny luster, with obvious striations or grooves, hard and dense: Quartz is common, but often not visible:

Texture - Foliated
Grains NOT Visible

May have shiny luster, obvious striations or grooves, hard and dense	Quartz may be visible	

Your Rock is Mylonite!

MYLONITE

The formation of mylonites (fault rocks) is complex and involves successive stages of deformation, recovery, and recrystallization. During deformation, pressure solution may contribute to fabric development, but deformation processes are basically mechanical in nature. Mylonitization also involves the chemical processes of metasomatism and recrystallization. In these, as well as in the deformation processes, fluids are important. Other variables that control the nature of the mylonitization include the nature of the protolith, the confining pressure, the temperature, and the continuity of the rock mass.

The deformation processes involved in mylonitization include microfracturing, twinning, dislocation glide, and grain-boundary sliding. Microfracturing is a process in which microscopic fractures develop within and between grains, in response to stress. In minerals with cleavage, the intragranular fractures may follow the cleavage. Feldspars, in particular tend to fracture during mylonitization, and in some cases, quartz, calcite, olivine, pyroxene, and biotite do so as well. Twinning is another mechanism by which crystals may reflect strain. Dislocation glide refers to a shift in the position of a defect within a crystal lattice. The defect may change size or may simply change positions. Grain-boundary sliding is a process in which grains shift positions relative to adjoining grains, with the shift occurring along the grain boundary. All of these processes are granular adjustments made within rocks to accommodate an applied stress. The adjustments result in a foliated rock.

In addition to the mechanical processes of deformation involved in mylonite formation, recrystallization, and metasomatism are important in the development of the character of these rocks. Recrystallization is the process in which strain energy is reduced by the nucleation and growth of new crystals within and at the margins of host crystals. Fluid flow in fault zones and ductile deformation zones is significant in promoting mechanical deformation and recrystallization. Major metasomatic effects are also produced by fluids. For example, fluids have removed more than 60% of the volume of material in some mylonite zones. Pressure solution promotes some of this volume loss.

Together, combinations of the processes described above yield mylonitic rocks. The particular combination of processes that produces the specific fabric elements and mineral composition of any given mylonite is a function of the rock and fluid composition and the strain history.

Nonfoliated texture. Nonfoliated rocks will appear as massive and structureless. They exhibit a nonfoliated character because the original rocks (protolith) were composed of equant grains that tended to grow equally in all directions and form an interlocking, dense, crystalline mosaic. .

Texture - Nonfoliated

Step 2

COLOR/PROPERTIES	MINERALOGY
Shiny Black	Coal (no minerals)
Light colored , fizzes with acid	Calcite
Various colors, scratches glass	Quartz

1- Shiny Black:

Texture - Nonfoliated

Black with a shiny luster	Does not easily soil fingers, may have a concoidal fracture	

Your Rock is Anthracite!

ANTHRACITE

Anthracite, often called HARD COAL, is a highly metamorphosed variety of coal. It contains more fixed carbon (about 90 to 98 percent) than any other form of coal and the lowest amount of volatile matter (less than 8 percent), giving it the greatest calorie, or heat, value. Because of this, anthracite is the most valuable of the coals. It is, however, also the least plentiful. Anthracite makes up less than 2 percent of all coal reserves in the United States. Most of the known deposits occur in the eastern part of the United States.

Anthracites are black and have a brilliant, almost metallic lustre. They can be polished and used for decorative purposes. Hard and brittle, anthracite breaks with conchoidal fracture into sharp fragments that are clean to the touch. Although anthracite is difficult to ignite, it burns with a pale-blue flame and requires little attention to sustain combustion. Anthracite is particularly adaptable for domestic use because it produces little dust upon handling and burns slowly while emitting relatively little smoke. It is sometimes mixed with bituminous coal for heating factories and other commercial buildings to reduce the amount of smoke produced but it is seldom used alone for this purpose because of the high cost.

2- Light colored , fizzes with acid:

Texture - Nonfoliated

White, cream, pink or light blue	Reacts with acid, crystalline appearance	

Your Rock is Marble!

MARBLE

Marble is a granular limestone or dolomite that has been recrystallized under the influence of heat, pressure, and aqueous solutions. Commercially, it includes all decorative calcium-rich rocks that can be polished, as well as certain serpentines. Marbles are massive rather than layered and consist of a mosaic of interlocking calcite grains. They often occur interbedded with such metamorphic rocks as mica schists, phyllites.

Most of the white and gray marbles of Alabama, Georgia, and western New England are recrystallized rocks, as are a number of Greek and Italian statuary marbles famous from antiquity. These include the Parian marble, the Pentelic marble of Attica in which Phidias, Praxiteles, and other Greek sculptors executed their principal works, and the snow-white Carrara marble used by Michelangelo and Antonio Canova and favored by modern sculptors. The exterior of the National Gallery of Art in Washington, D.C., is of Tennessee marble, and the Lincoln Memorial contains marbles from Colorado, Alabama and Georgia.

Even the purest of the metamorphic marbles contain some accessory minerals. The commonest are quartz in small rounded grains, scales of colorless or pale-yellow mica (muscovite and phlogopite), dark shining flakes of graphite, iron oxides, and small crystals of pyrite. Many marbles contain other minerals that are usually silicates of lime or magnesia. Diopside is very frequent and may be white or pale green; white bladed tremolite and pale-green actinolite also occur; the feldspar encountered may be a potassium variety but is more commonly a plagioclase (sodium-rich to calcium-rich) such as albite, labradorite, or anorthite.

These minerals represent impurities in the original limestone, which reacted during metamorphism to form new compounds. The alumina represents an admixture of clay; the silicates derive their silica from quartz and from clay; the iron came from limonite, hematite, or pyrite in the original sedimentary rock. In some cases the original bedding of the calcareous sediments can be detected by mineral banding in the marble. The silicate minerals, if present in any considerable amount, may color the marble; e.g., green in the case of green pyroxenes and amphiboles; brown in that of garnet; and yellow in that of epidote and sphene. Black and gray colors result from the presence of fine scales of graphite.

3- Various colors, scratches glass:

3-1: Shiny , white or light gray:

Texture - Nonfoliated

Scratches Glass

White, light gray, pink or blue	Quartz grains welded together (hard), breaks across grains	

Your Rock is Quartzite!

3-2: Dark gray, green, brown:

Texture - Nonfoliated

Scratches Glass

Various shades of gray, or gray-green	Dense, dull (not shiny), may be spotted	

Your Rock is Hornfels!

HORNFELS

Hornfels are rocks that form by contact metamorphism in the inner parts of the contact zone around igneous intrusions. All of the rocks called hornfels--a hard, fine-grained, flinty rock--are created when heat and fluids from the igneous intrusion alter the surrounding rock, changing its original mineralogy to one that is stable under high temperatures. Temperatures as high as 700 - 800deg C may be reached, depending upon the pressure at the depth of the intrusion. The minerals of the hornfels facies depend largely upon the composition of the parent rock.

Gemstone

- **Andalusite**
- **Apatite**
- **Beryl**
  - Clear
  - Yellow
  - Green
- **Cordierite**
- **Feldspar**
  - Orthoclase
  - Labradorite
  - Sunstone
  - Moonstone
- **Fluorite**
- **Garnet**
  - Almandine
  - Pyrope
  - Rhodinite
  - Spessartine
  - Tsavorite
  - Malaysian
- **Lapis**
- **Malachite**
- **Opal**
  - Solid
  - Brazilian
  - Triplets
  - Slocum Stone
- **Peridot**
- **Quartz**
  - Caringorm
  - Amethyst
  - Citrine
  - Amatrene
  - Dentritic
  - Tourmalated
  - Rutilated
  - Agate
  - Fire Agate
  - Onyx
  - Bloodstone
  - Carneilian
  - Aventurine
  - Sardonyx
- **Sapphire**
  - Yellow
  - Blue
  - Lavender
  - Green
- **Scapolite**
- **Spinel**
- **Sugilite**
- **Tanzanite**
- **Topaz**
  - Clear
  - Imperial
  - Blue
  - Root beer
  - Rutillated
- **Tourmaline**
  - Indicolite
  - Rubellite
  - Green
  - Yellow
  - Orange
  - Watermelon
  - Bi & Tri color
- **Turquoise**
  - Morenci
  - Green
  - Blue
- **Synthetics**
  - Cubic Zirconia
  - Spinel
  - Corundum
  - Strontium Titanate
  - Fiberlite
  - Linde
  - Chatham
- **Zircon**

Name:	Andalusite		
Chem:	Al_2SiO_5 Aluminum Silicate		
Crystal:	Orthorhombic (Large size gem quality crystals are rare.)		
Color:	Strong pleochroism one axis/yellow-olive other axis/brown-red		
Refrac. Index:	1.63 - 1.648	**Birefraction:**	0.006
Hardness:	7.5 (gem quality)	**Spec. Grav.:**	3.12 - 3.18
Fracture:	conchoidal	**Cleavage:**	imperfect
Environment:	Found in pegmatites, gneiss, hydrothermal deposits, and gem gravel		
Association:	quartz, muscovite, microcline, cordierite, topaz		
Locals:	| Brazil | Sri Lanka | Canada | Spain |		
Misc:	the name is from a region in Spain (Andalucia), it is one member of three minerals with the same composition, andalusite, sillmanite, and kyanite.		
Gem info:	It is mainly a collectors item, and has not seen wide use in the jewelry trade, there is another variety called chiastolite that forms long prismatic crystals with a black cross in its cross section. The name comes from the Greek "chiastos" meaning "X-marked". It was used as an amulet by early Christens.		

Name:	**Apatite**		
Chem:	$Ca_5(F,Cl,OH)(PO_4)_3$ Calcium Fluoro-Phosphate		
Crystal:	hexagonal (prism very common)		
Color:	colorless, blue, green, yellow, violet		
Refrac.Index:	1.63 - 1.646	**Birefraction:**	0.003
Hardness:	5	**Spec. Grav.:**	3.17 - 3.23
Fracture:	conchoidal	**Cleavage:**	poor
Environment:	stable in many environments, hydrothermal veins, metamorphics, and even via chemical deposition		
Association:	pegmatites, al manner of metamorphics		
Locals:	| Brazil | Sri Lankra | Canada | Maine, USA |		
Misc:	from the Greek word "apatos" meaning "deception", because of its wide variety of colors and crystals shapes. soluble in HCl, often fluorescent or thermoluminescent. Used mainly as a source of phosphates for fertilizer.		
Gem info:	The green variety is sometimes called "asparagus stone", it is not common in the jewelry trade because it is both soft and very brittle. Mainly purchased by gem collectors.		

Name:	**Beryl**					
Chem:	$Al_2Be_3(Si_6O_{18})$ Aluminum Beryllium Silicate					
Crystal:	Hexagonal (often long prisms					
Color:	blue aquamarine	green emerald	yellow heliodor	violet-pink morganite	colorless goshenite	red bixbite
Refrac. Index:	1.57 - 1.60		**Birefraction:**	grn/blue-0.006 yel-0.005		

			others-0.008
Hardness:	7.5	**Spec. Grav.:**	2.69 - 2.8
Fracture:	conchoidal	**Cleavage:**	imperfect
Environment:	granite rocks and pegmatites, hydrothermal deposits		
Association:	quartz, spodumeme, cassiterite, columbite and other rare minerals		
Locals:	| Columbia | Brazil | Russia | Australia | Mass., Calif., USA | Sri Lankra | Namibia |		
Misc:	the name comes from the Greek "berylos", and which means "sweet.". Some varieties fluorescent, insoluble in acids, a very important economic mineral and the major source of beryllium.		
Gem info:	An important series of gemstones, Emerald is one of the most expensive stones on the market, the best comes from Columbia and is colored by chromium impurities. The chromium weakens the crystal lattice and produces a highly flawed structure, which makes the stone weak and easily damaged by mechanical force.. It is sometimes oiled to hide the internal flaws. The best blue, Aquamarine, comes from Brazil today, and can be found in very large, and very clean crystals. The color is caused by iron impurities, and it can be heat treated to enhance the color. It is more expensive than blue topaz, but far less expensive than emerald. Asterism is possible in aqua producing either cats-eye or even star stones. The rarest beryl is bixbite (red) and is not usually seen in jewelry as it occurs in only very small crystals. The red color is due to manganese, and the best material comes from Utah. Heliodor (yellow-green) is colored by uranium and is slightly radioactive. Yellow to yellow-orange samples are referred to as golden beryl. True Heliodor is valued by collectors but not seen much in jewelry, the golden beryls are seen often in jewelry but are not as expensive as aquamarine. Morganite (pink) is one of the more expensive beryls and like virtually all good pink stones draws an excellent price, again not as expensive as emerald, but equal to the best aquamarine. It contains cesium and lithium, but the color agent is a trace of manganese. Goshenite (clear-colorless) - often used with a metal foil to imitate emerald or aquamarine. Is not used extensively in jewelry and is not expensive.		

Name:	**Cordierite (Iolite)**		
Chem:	**$Mg_2Al_3(AlSi_9O_{18})$**		
Crystal:	Orthorhombic (often short prisms)		
Color:	Strongly dichroic or trichroic blue - yellow - gray		
Refrac. Index:	1.53 - 1.55	**Birefraction:**	0.008 - 0.012
Hardness:	7 - 7.5	**Spec. Grav.:**	2.58 - 2.66
Fracture:	conchoidal	**Cleavage:**	imperfect
Environment:	found in aluminum rich metamorphic rocks		
Association:	quartz, andalusite, sillmanite, biotite, spinel, corundum		
Locals:	| Conn., N.Y., N.H., Calif., USA | Brazil | Sri Lanka | Burma |		
Misc:	One of the names comes from the Greek "ion", meaning "violet", while the name cordierite comes from the French geologist, Pierre Louis Cordier. Another common name is "dichroite" from its strong dichroic nature. Insoluble in acids.		
Gem info:	The gem trade has yet another name for this mineral "water sapphire". It is usually cut so that the strongest blue color comes up through the top of the stone. It often shows gray overtones which can detract from its appearance. It is used sparsely in jewelry, and is more of a collectors stone.		

Name:	**Feldspar**		
Chem:	**KAlSi$_3$O$_8$** - Orthoclase **KAlSi$_3$O$_8$** - Microcline **NaAlSi$_3$O$_8$**- **CaAl$_2$Si$_2$O$_8$** - Plagioclase		
Crystal:	Orthoclase - monoclinic (prismatic crystals, often flat sided crystals) Microcline - triclinic(prismatic, and often twinned) Plagioclase - triclinic(often flat or tabular with striations)		
Color:	Orthoclase - usually light colored white, pink, yellow, or cream, and not transparent. The gem variety is clear to pale yellow, and some called "noble orthoclase" Microcline - white, pink, pale yellow, or sometimes green-blue, and not transparent. The green-blue variety is called "amazonite" Plagioclase - gray to grayish-white is common, but may also be white, pink or pale yellow. More semi-opaque than the other feldspars on average, and contains striations on some crystal faces or cleavage surfaces.		
Refrac. Index:	O 1.52-2.54, M 1.52-1.53, P 1.53-1.59	**Birefraction:**	O-0.005, M-0.008, P-0.010
Hardness:	6-6.5	**Spec. Grav.:**	(O-M)-2.56 , P-2.64-2.70
Fracture:	All-uneven	**Cleavage:**	All-perfect
Environment:	the feldspars make up the major constituent of many igneous and metamorphic rocks, they form at medium to high temperature and at some depth. Microcline can form in granite pegmatites and at lower		

	temperatures.
Association:	quartz, other feldspars, hornblende
Locals:	| all over the world Amazonite-Brazil, Col., USA | Labradorite - Labrador, Norway | Sunstone - Ore., USA | Gem Orthoclase - Madagascar |
Misc:	The word comes from the German "feldt spat", meaning "field spar", "spar" meaning common clevable material - the material dredged up on farm lands during plowing. Most of them are not affected by acid (exception the Ca rich plagioclase - Anorthite). Orthoclase got is name from the Greek phrase meaning "straight fracture", Microcline from a Greek phrase meaning "small incline", and Plagioclase from the Greek phrase meaning "oblique fracture".
Gem info:	Orthoclase - when transparent it is faceted into a gemstone. Clear or pale yellow in color it is a collectors item, and of little value to the jewelry industry as both beryl and even citrene are harder and more durable. Microcline - variety amazonite, is sometimes cut into cabochons, and used in jewelry. The blue-green color is caused by a lead impurity. It is rarely used as more people are aware of turquoise and chrysocolla. Moonstone - moonstone can be made up of any number of different feldspars including, orthoclase, plagioclase, albite, and microcline. They are all very similar when cut into cabochons, they can best be distinguished by their different densities. Moonstone tends to be silver, pale green, pale blue, or creamy colored. It is translucent and shows a blue-white sheen sometimes called "adularescence". Plagioclase - there are two distinct varieties used in jewelry, the dark-blue-black Labradorite, and the orange-honey colored Sunstone. • Labradorite gets its coloring from a "labradorescence", reflected light from a multitude of small parallel, plate-like structures, with minute inclusions of ilmenite, rutile, and magnetite. The color patterns are similar in that shown in nature with oil on

	water. It is rarely faceted, but often cut into attractive cabochons. Value is not really very high as it has not caught on as a popular material and is abundant. • Sunstone is a species of plagioclase called "oligoclase" or known sometimes in the jewelry industry as "adventurine feldspar". It gets is shiller in the same way that labradorite does, but the background color is brown to orange, and the composition is full of small hematite crystals that give it additional sparkle.

Name:	**Fluorite**		
Chem:	**CaF_2** Calcium Fluoride		
Crystal:	Cubic (cubes, octahedrons, dodecahedrons)		
Color:	clear, blue, yellow, purple, pink, green, brown, orange		
Refrac. Index:	1.43	**Birefraction:**	none
Hardness:	4	**Spec. Grav.:**	3.18
Fracture:	even to conchoidal	**Cleavage:**	perfect
Environment:	hydrothermal veins, pegmatites, sublimation product in some volcanics		
Association:	quartz, cassiterite, topaz, apatite, sulfides,		
Locals:	| Italy | Switzerland | Brazil | Germany | Canada | Ill., Ken., USA |		
Misc:	From the Latin "fluere", meaning" to flow". It was used in ancient times as a flux. Contact with sulfuric acid		

	releases HF gas (**very toxic!**) Often fluorescent in UV.
Gem info:	Used by ancients to carve bowls, vases, goblets etc. It is extremely soft and can only be used in jewelry if very well protected. It also has perfect cleavage making it subject to easy fracture. There has recently been a number of cut stones in the market coming from China. It is very inexpensive, but the cut stones tend to be fairly large.

Name:	**Garnet Family**		
Chem:	$\mathbf{Mg_3Al_2(SiO_4)_3}$ - $\mathbf{Fe_3Al_2(SiO_4)_3}$ - $\mathbf{Mn_3Al_2(SiO_4)_3}$ Pyrope - Almandine - Spessartite		
Crystal:	Isometric (rhombic, dodecahedron, isoctohedron, and trapezohedron)		
Color:	red, red-brown, black, green, orange, purple, yellow		
Refrac. Index:	1.69 - 1.86	**Birefraction:**	0.022 - 0.057
Hardness:	6.5 - 7.5	**Spec. Grav.:**	3.6 - 4.2
Fracture:	conchoidal	**Cleavage:**	imperfect
Environment:	garnets area solid solution series, and occur in contact metamorphics, serpentines		
Association:	scapolite, diopside, calcite, wollastonite, kimberlite, tremolite		
Locals:	| Italy | Turkey | Calif.., N.J., N.C., Col., USA | Sri Lanka | Norway | Bohemia |		
Misc:	The name almandine comes from the Anotolian city of Alabanda; the name Andradite comes from the Brazilian mineralogist J.B. d'Andrada; the name Grossular comes from the Greek "grossularia", "meaning gooseberry"; the name Pyrope comes from		

	the Greek "pyropos", meaning "fire-eyed" for its red color; the name Spessartite comes from Spessart mining district in Bavaria; and the name Uvarovite comes from the Russian noble man, Count Sergei Uvarov. The garnets make up two solid solution series; 1) pyrope-almandine-spessarite and 2) uvarovite-grossularite-andradite. The majority of garnet goes into the manufacture of sand-paper.
Gem info:	Almandine is the deep-red iron rich garnet and often cut into ovals. If the stone is deep it may appear too dark and has less value. Much of the older Victorian jewelry used these garnets. Pyrope is a fiery red garnet, but it too may suffer from being too dark. Large stones are often available but it is not one of the more highly priced gems. "Rhodolite" is a special variety of the Almandine-Pyrope mix. It is about 1/2 way between the two end members and is a reddish-purple stone usually with good clarity. It is very popular today, and is among the more expensive of the red garnets. It is still not in the price range of good imperial topaz, aquamarine or good tourmalines. It is a second tier stone. Spessartite is a manganese rich variety that may be orange to orange-brown in color and large stones are usually not available. It is priced above Almandine and Pyrope and about the same level as rhodolite. Grossular garnets come manly in a yellow color from Sri Lanka. It also comes in a yellow-brown variety with the name "Hessonite" (from the Greek "esson", meaning inferior). Today the most prized member of the garnet family is the green grossular garnet called "Tsavorite" from near the Tsavo National park in Kenya. This green garnet gets it's color from chromium just like emerald. It is sold as an emerald substitute and brings a quality price. Large stones above 3 carats are very uncommon. Andradite garnet is usually black and of no interest to the gem trade, but one variety called "Demantoid" is a lively green. It is a little on the softside and very brittle so it needs good protection in jewelry. It brings

	a premium price, but is available only in small stones. Uvarovite rarely occurs in facetible sizes, but when it does it makes a spectacular stone. If it is emerald green in color it can bring a hefty price. If too dark, it not worth nearly as much.

Name:	**Lapis Lazuli (Lazurite)**		
Chem:	**$(Na,Ca)_8(Al,Si)_{12}O_{24}S_2$ - FeS - $CaCO_3$** **Sodium Calcium AluminoSilicate - (with pyrite&calcite)**		
Crystal:	Isometric (usually not crystalline, instead aggregate masses)		
Color:	blue		
Refrac. Index:	1.50	**Birefraction:**	None
Hardness:	5 - 6	**Spec. Grav.:**	2.4 - 2.9
Fracture:	conchoidal	**Cleavage:**	none
Environment:	lazurite is the primary mineral, but lapis lazuli is a physical mixture of calcite, pyrite, lazurite and other minerals to a lesser degree. Found as veins in limestone, and created at the contact metamorphic zone of marbles.		
Association:	pyrite, calcite, augite, diopside, hornblende		
Locals:	| Afghanistan | Chile | Russia | Calif., USA |		
Misc:	The names comes from the Persian "lazuward", meaning "blue". It was the main coloring agent for ultramarine blue pigment, but has now been surpassed by synthetic colorants. It is easily damaged by both acids and strong base.		
Gem info:	Lapis has been mined for more than a thousand years as an ornamental stone, and was found in the possessions of Tutankhamen. It is usually cut into cabochons, or		

	geometric shapes. It is also prized for carving. About on par with turquoise and jade in price.

Name:	**Malachite**		
Chem:	$\mathbf{Cu_2CO_3(OH)_2}$ basic copper carbonate		
Crystal:	Monoclinic (usually not crystalline, often botryoidal masses)		
Color:	light green --> dark green		
Refrac. Index:	1.65 - 1.91	**Birefraction:**	0.021
Hardness:	4	**Spec. Grav.:**	3.8
Fracture:	splintery	**Cleavage:**	perfect
Environment:	oxidation zone of copper deposits		
Association:	azurite, limonite, chalcopyrite		
Locals:	| Ar., Calif., Nev, USA | Zaire | Chile | USSR |		
Misc:	The name derived from the Greek word "malache", meaning "mallow" in reference to its green color or "malakos", meaning soft. Easily damaged by acids like all carbonates, and when subjected to heat it turns black.		
Gem info:	Cut stones (usually cabochon) have been used since ancient Egyptian times as amulets, carvings, and even as powder for eye shadow. It has been used as a pigment for green paint. Today the best material comes from Zaire, Africa, is cut into cabs of all sizes. Less valuable than turquoise, jade, and lapis.		

Name:	**Opal**		
Chem:	**SiO_2-n(H_2O)** hydrated silica		
Crystal:	Isomorphic (no crystal structure)		
Color:	yellow, clear, blue, gray, (all with or without color flash)		
Refrac. Index:	1.44 - 1.46	**Birefraction:**	none
Hardness:	5.5 - 6.5	**Spec. Grav.:**	1.98-2.20
Fracture:	conchoidal	**Cleavage:**	none
Environment:	opal is a low temperature mineral and is found in cracks or cavities that are filled in late in their geological life. Water , must be present. It is also found as a replacement after certain skeletons of marine animals or plants.		
Association:	often in porous substrates		
Locals:	| Australia | Calif., Nev., Idaho, USA | Mexico | Brazil | Hungary |		
Misc:	The name is probably from the Latin "opalus", meaning "precious stone". Opal can easily be dehydrated by heat or chemical exposure. Is very porous and can be damaged by many chemicals. Opal has been duplicated in the laboratory, and the material provides a very close approximation to the natural material. It is produced by the controlled (very slow) precipitation, and alignment of small silica spheres. The spheres form a three dimensional diffraction pattern which produces the color play. Beside synthetic opal there are also some opal "simulants" on the market. A simulant is something that resembles the natural material, but is composed or produced in an entirely different way. One such simulant is "Slocum Stone", and appears to be a variety of glass. (See Synthetics for more man-made stones.)		
Gem info:	Opal has a variety of poor gemstone characteristics, softness, dehydration, cracking, physical weakness,		

and sensitivity to heat. It also shows one of the best spectral displays of any gemstone, hence its value. It is made up of layers of precipitated silica spheres in a jelly-like water mass, and the ordering of the spheres sometimes produce a diffraction grating, that creates a play of rainbow sparkling light from within the stone.

There are fundamentally three types of opal: precious opal (containing flashes of fire), the yellow-reddish "fire opal" which is named for its color (not flashes of fire), and common opal (sometimes called "potch").

"Common opal" is rarely transparent, but may be colored or contain inclusions. It is used as backing for the more desirable varieties of precious opal, but may also be cabbed to produce interesting stones. It comes in white, gray, yellow, blue, green, pink, and may be dendritic or contain moss.

"fire opal" is named for its fiery red color, and not the flashes from within. Today most fire opal comes from Mexico and is often cut into faceted gem stones. It runs from a deep red to many shades of orange and even on to yellow. It may have a few flashes of fire, but usually it is sold for the color and clarity. It is not particularly expensive as it suffers from the same physical characteristics as all opal, and contains little of the desired color flash.

"Precious Opal" - this is the material with the internal "color play", "flash", or "light show". It is classified by its back ground color, the particular colors and intensity of color display, and its size. Stones that are predominantly white or light blue are the most common, and those that contain reds, oranges, and violets are considered more desirable. Blue and green are very common in most precious opal. Black opal, opal containing a predominantly dark background (dark-gray to blue-black) is the rarest, and most desired of all opals. When it contains reds and oranges it brings even a higher value. It may be priced right up with the top gemstones (diamond, emerald, and ruby). The very best black opal came from Lightening Ridge. Australia and small amounts till reach the market today, but there have been no major

	finds in many years. Another "collectors" variety is called "contra luz". It shows the desired play of color, but only when light is transmitted through the stone. It appears to be clear when viewed from the same side. It is thus very difficult to design jewelry using this variety and it finds its way mainly into collections. "Hydrophane" is a variety that losses its water to become opaque, but can regain it's water and become transparent with color flash, again mainly a collectors stone. Opal Doublets and Opal Triplets - these are sandwiched stones made up of 2 or more pieces. Further information is provided.

Name:	**Peridot (Olivine)**		
Chem:	$\mathbf{Mg_2SiO_4}$-forsterite $\mathbf{(Mg, Fe)_2SiO_4}$ - olivine (Peridot) $\mathbf{Fe_2SiO_4}$ - fayalite		
Crystal:	Orthorhombic (Usually glassy rounded grains, crystals are rare.)		
Color:	light green, dark green, olive green, yellow-brown, and rarely reddish		
Refrac. Index:	1.65-1.69	**Birefraction:**	0.036
Hardness:	6.5- 7	**Spec. Grav.:**	3.27 - 3.37
Fracture:	brittle	**Cleavage:**	imperfect
Environment:	a rock forming mineral and often present in basalt and volcanic ejecti.		
Association:	basalt, gabbro and peridotite		
Locals:	| St. Johns Island | Ar., N. M., USA | Burma | Australia | Norway |		

Misc:	it is soluble very slowly in hydrochloric acid yielding a gel. Most of the gem variety is predominantly foresterite, named for the German naturalist, Johnn Forester.					
Gem info:	Peridot has been mined on St. John's Island (known in Arabic as Zibergit) for more than 3000 years. At one time it was known as Topazion and the gem was topazos. Now the name topaz is given to an entirely non-related gem. Peridot may be from the Arabic, "faridat" which means gem. It is also known as chrysolite from the ancients "chrysolithos", meaning "golden stone". It has an oily look which looks something like olive oil. Good crystals are more valuable than cut stones, so are usually purchased by mineral collectors. Small cut stones are very common (less than 2-3 carats) and not expensive. Stones over 5 carats begin to climb in value, and those above 10-15 carats my be pricey as they are rare.					

Name:	**Quartz**					
Chem:	**SiO$_2$** - Silicon Dioxide					
Crystal:	Hexagonal (excellent hexagonal prisms with termination, also massive, and crypto-crystalline varieties)					
Color:	purple amethyst pink rose	yellow - orange citrene	clear rock crystal	gray-brown cairngorm	crypto-crystalline agate jasper	
Refrac. Index:	1.54 - 1.55		**Birefraction:**		0.009	
Hardness:	7.0		**Spec. Grav.:**		2.65	

Fracture:	conchoidal	**Cleavage:**	none	
Environment:	a rock forming mineral, contact metamorphics, hydrothermal, mesothermal, and epithermal veins			
Association:	feldspars, pyrite, tourmaline, rutile			
Locals:	| Largest crystals, Brazil | found virtually everywhere | Ark., USA |			
Misc:	The name is derived from the German "quarz" of Slavic origin. It was called "krystallos" by the Greeks, but this later became the generic term for crystal. It is used as an oscillator in time pieces and in radio, and was mined extensively in brazil during W.W.II. The material has now been synthesized in the laboratory and is much purer and better for electronic use.			
Gem info:	Quartz is the most abundant mineral on earth and is present in many rock types. It is classified by both color and physical makeup. First there are two physical types: 1.) crystalline (natural and synthetic) 2.)cryptocrystalline **Crystalline:** meaning large single crystals of aggregates of individual crystals. Having the hexagonal shape or habitat of the mineral. (Rose quartz is a minor exception as it rarely forms good crystals.) • **Amethyst:** lilac or purple quartz gets its color from an iron impurity (Fe+3), it is the most valuable of the quartz			

gem stones. The best quality is dark purple with a red-flash. At one time it was one of the most expensive stones on earth, but with the huge finds in the new world (especially Brazil) the price plummeted.

- **Citrene:** yellow to orange in color, citrene gets its color from an iron impurity too, and heating amethyst to 550 degrees centigrade converts it to citrene. Subjecting citrene to radiation can re-convert it to amethyst. Heat treated stones tend to have a red-tint. It is sometimes passed off as a form of topaz being called "bahia-topaz" , "golden topaz" or "Madeira topaz". All of these materials a quartz and NOT topaz. Citrene is typically not as expensive as amethyst, so is usually very inexpensive.
- **Smoky Quartz:** smoky quartz gets its color from irradiated impurities which have a smoky area around them. The term "cairngorm" is used to describe the variety found in the Cairngorm Mountains of Scotland. It is very inexpensive in cut stones, less than $1 per carat.
- **Rose Quartz:** this is one of the more rare types of crystalline quartz, it is usually somewhat cloudy due to the inclusion of rutile crystals. Large cut stones are rare, and even small ones tend to be cloudy looking. It tends to have more value as a carving material.

Cryptocrystalline: masses made up of either fibrous or granular aggregates of quartz. Both are tough and compact, and take a good polish when cabbed.
Chalcedony: the general term used to describe the fibrous variety of cryptocrystalline quartz.

- **Agate:** usually a banded material that is translucent and may contain any number of colors or combinations. It may also include members that are non-banded, but contain dendrites in the form of moss or other organic-like structures.
- **Carnelian and Sard:** are solid colored, but translucent chalcedony that are in the red to brown end of the spectrum
- **Aventurine :** A greenish quartz with fuchite mica or other metallic looking inclusions that make the material "sparkle".
- **Bloodstone :** Also known as heliotrope or plasma, is an opaque green chalcedony with red iron oxide inclusions that resemble blood.

- **Chrysophrase:** a green variety of chalcedony colored by the element nickel. The best material is now coming from Australia.
- **Onyx:** a variety of agate with parallel bands of color that are linear and not in the form of curves. (There is a variety of marble that is sometimes called onyx, but is much softer and easily damaged by acid.)

Jasper, Flint, and Chert are names used to describe some of the varieties of granular quartz.

- **Jasper:** it is the granular counterpart of carnelian and sard, and is usually brown, red, yellow, and may have inclusions of metal oxides. The name derived from the Greek and means "spotted stone". Sometimes as parallel lines rather than spots. Several varieties can create what looks like miniature landscape scenes and are often referred to as "picture jaspers".
- **Flint and Chert:** non-gem varieties of cryptocrystalline-granular quartz. They chip very easily and thus can be made to hold and edge. Used mainly in the manufacture of arrow heads and stone knives.

Name:	**Sapphire (Corundum)**		
Chem:	**Al_2O_3** - Aluminum Oxide		
Crystal:	Hexagonal (sometimes tapering crystals)		
Color:	Sapphires may be all colors except red, if red it is called ruby. Common colors, clear, blue, pink, green, yellow, violet.		
Refrac. Index:	1.76 - 1.77	**Birefraction:**	0.008
Hardness:	9.0	**Spec. Grav.:**	3.9 - 4.1

Fracture:	uneven	**Cleavage:**	none
Environment:	it occurs in nepheline syenite pegmatites, contact metamorphics, and hornfels		
Association:	albite, andalusite, cordierite, muscovite, oligoclase		
Locals:	| Mon., N.C., USA | Canada | Thailand | Australia |		
Misc:	The mineral name Corundum comes from Sanskrit "kuruntam", "red-stone or ruby". The name Ruby comes from the Latin "ruber", meaning "red". The name Sapphire comes from the Sanskrit "sanipriya", which means "dear to the planet Saturn". Insoluble in acids. Poor qualities are used as an abrasive, and it is made synthetically.		
Gem info:	In general all colors of corundum that are not RED are called sapphire. This is done so that there are no poor grades given to light pink stone. It is not a poor quality ruby, it is a pink sapphire. The most desired color is called "corn-flower blue", and any traces of gray detract from the value. There is one special variety , an orange-pink stone (very rare) called Padparadscha (which is a Sinalese word for "lotus blossom". Sapphires fall behind diamond, emerald, and ruby is price, but not much. The non-blue stones are worth substantially less. Of the other colors the special Padparadscha and pink stones are the most expensive.		

Name:	**Scapolite**		
Chem:	**$Na_4(AlSi_3O_8)_3Cl.nCa_4(Al_2Si_2O_8)_3(SO_4,CO_3)$** complex sodium calcium aluminum silicate		
Crystal:	Tetragonal (usually short prisms with square cross section)		
Color:	clear, yellow, green, gray, and rarely violet, blue, or pink		
Refrac. Index:	1.54 - 1.58	**Birefraction:**	0.020
Hardness:	5 - 6.5	**Spec. Grav.:**	2.57 - 2.74
Fracture:	conchoidal	**Cleavage:**	perfect (2 directions)
Environment:	a metamorphic product, hydrothermal metamorphic rocks.		
Association:	almandine, andalusite, andradite, actinolite, microcline, muscovite		
Locals:	| Canada | N.Y., N.J., USA | Brazil | Switzerland | Mexico |		
Misc:	The name comes from the Greek "skapos", meaning "shaft" alluding to its common long prismatic form. Often fluorescent orange-yellow. Soluble in HCl leaving silica. Also known as wernerite named for a German explorer.		
Gem info:	The transparent varieties are faceted and the less transparent stones may be cabbed yielding some cats-eye stones. The value increases with the darker colors, but it is not an expensive stone.		

<table>
<tr><td colspan="4"></td></tr>
<tr><td>Name:</td><td>Spinel</td><td colspan="2" rowspan="4"></td></tr>
<tr><td>Chem:</td><td>$MgAl_2O_4$ -
Magnesium Aluminum Oxide</td></tr>
<tr><td>Crystal:</td><td>Isometric (usually in octahedrons or cubes)</td></tr>
<tr><td>Color:</td><td>color: pink, violet, red, yellow, orange, blue, green, black, brown</td></tr>
<tr><td>Refrac. Index:</td><td>1.71 - 1.74</td><td>Birefraction:</td><td>None</td></tr>
<tr><td>Hardness:</td><td>8.0</td><td>Spec. Grav.:</td><td>3.58 - 3.61</td></tr>
<tr><td>Fracture:</td><td>conchoidal</td><td>Cleavage:</td><td>imperfect</td></tr>
<tr><td>Environment:</td><td colspan="3">found mainly in metamorphics rocks</td></tr>
<tr><td>Association:</td><td colspan="3">olivine, hornblende, phlogopite, chondrodite</td></tr>
<tr><td>Locals:</td><td colspan="3">| Ceylon | Burma | Canada | N.Y., N.J., Calif., USA | Brazil | Pakistan | Sweden |</td></tr>
<tr><td>Misc:</td><td colspan="3">The origin of the name is uncertain but probably comes from the Latin "spina", meaning "thorn", in reference to sharply pointed crystals. It is an excellent refractory material and has been used in many high-temperature applications. It has been synthesized since 1910 and is now available in more synthetic colors than natural colors.</td></tr>
<tr><td>Gem info:</td><td colspan="3">Good quality red spinel is difficult to tell from ruby, and for years a large red-stone in the British Crown Jewels was identified as the Black Prince's Ruby", but was eventually discovered to be a red spinel.

Several colors have trade names, purple spinel is called "almandine spinel", very dark blue-green stones are called "pleonast", and orange-pink spinel is called "rubicelle". Although none of these are common names, they may be refereed to in some cultures.

Good red spinels and good blue spinels command prices near the top of the secondary market, but are not anywhere near on par with their ruby and sapphire counter parts. Pink spinels, and other pale colors have far less value.</td></tr>
</table>

Name:	**Sugilite**		
Chem:	**$KNa_2Li_3(Fe,Mn,Al)_2Si_{12}O_{30}$** Potassium sodium lithium (Iron, Manganese, Aluminum) Silicate		
Crystal:	Hexagonal (crystals are very rare, usually massive)		
Color:	purple, orchid, brown, and black		
Refrac. Index:	1.60-1.61	**Birefraction:**	NA
Hardness:	6 - 6.5	**Spec. Grav.:**	2.75 - 2.80
Fracture:	subconchoidal	**Cleavage:**	one direction
Environment:	found in aegirine syenite		
Association:	albite, pectolite, titanite, allanite, zircon, apatite		
Locals:	| Iwagi Island, Shikoku, Japan | South Africa |		
Misc:			
Gem info:	The very best quality comes as a translucent material which is normally cabbed. It is finding use in jewelry with turquoise, malachite and lapis as associate stones and in intarsia. It has a value about the same as turquoise or good lapis.		

Name:	**Tanzanite (zoisite)**		
Chem:	**$Ca_2Al_3Si_3O_{12}(OH)$** Hydrous calcium aluminum silicate		
Crystal:	Orthorhombic (long striated crystals, also bladed crystals)		
Color:	gray, yellow brown, pink (thulite), blue-purple (tanzanite), greenish		
Refrac. Index:	1.69-1.70	**Birefraction:**	0.009
Hardness:	6 - 6.5	**Spec. Grav.:**	3.35
Fracture:	uneven	**Cleavage:**	perfect
Environment:	restricted to metamorphic rocks		
Association:	hornblende, almandine, glaucophane		
Locals:	| Norway (thulite) | Tanzania, East Africa | N.C., Calif., USA |		
Misc:	named for its locality, Tanzanite (from Tanzania) where the only transparent gem variety is found. Thulite is named after Thule, an archaic name for Norway. (strong pleochroism from blue-violet to violet)		
Gem info:	The gem variety, tanzanite, is a very rare gemstone as there is only one place it has ever been found. Tanzanite was found in this locality in 1967, and it is today about exhausted. The stone is said to have low tolerance to ultrasonics, and should not be subjected to this method of cleaning. Tanzanite is a fairly high valued gemstone and falls in a class just below the three big colored stones, emerald, ruby and sapphire (which it resembles). Tanzanite can be heat treated to enhance its color and remove any yellow or brown overtones. Thulite is a cabing material and is not found in transparent rough. It is usually pink to brown in color.		

Name:	**Topaz**			
Chem:	$Al_2(SiO_4)(F,OH)_2$ Hydroxy-fluoro-aluminum silicate			
Crystal:	Orthorhombic (prisms with multifaceted ends common)			
Color:	clear, blue, pink, orange-red, red-brown			
Refrac. Index:	1.61 - 1.638	**Birefraction:**	0.014	
Hardness:	8	**Spec. Grav.:**	3.53 - 3.56	
Fracture:	conchoidal	**Cleavage:**	perfect	
Environment:	It is a high temperature mineral usually found in igneous rocks and high temperature veins. Also in hydrothermal replacement deposits.			
Association:	beryl, quartz, rutile, orthoclase, albite			
Locals:	| Brazil | USSR | Utah, Calif., Co, N.H., USA | Sri Lanka | Mexico |			
Misc:	The name Topaz is thought to be derived from the name Topazion, the old name for the island of Zebergit (St. Thomas Island) in the Red Sea. The Sanskrit word "Tapas" means "fire". It is insoluble in acids. Some varieties are heat sensitive.			
Gem info:	Clear topaz has little value, and is quite prevalent. Some varieties can be irradiated to various shades of blue, and this acceptable in the trade. Most blue topaz on the market today is irradiated. There is a grayish variety of topaz that is sometimes cut to produce a stone called "champaign" topaz. Blue topaz is rare in nature, but easily created from clear material. There is an abundance on the world market, and very large, flawless stones are easily available. It is relatively low in value, about the same as good amethyst.. It is available in shades of blue from very light, through sky-blue, and on to almost an inky blue. Overtones of gray are not desirable, and further			

reduce its value.

Red-brown topaz is also common and found in Mexico and Utah, it makes a nice faceted stone, and some don't. It is sometimes called "rootbeer" topaz. Again it is not of high value. It is typically more expensive than citrene, and far less than morganite, or good golden beryl.

Imperial-topaz is the most prized, and is a red-orange to a pink-orange color. The color is due to the presence of hydroxyl ions, and hence this variety is heat sensitive, and it usually contains numerous flaws. Preferred colors make this stone about the same in value as good aquamarine.

Pink topaz is fairly rare, but highly valued. Green is another rare color, but highly valued. Although pink is occasionally found in jewelry, the green is very rarely found.

Many times smoky quartz (under the name "smoky topaz"), or citrene (under the name "Bahia or Maderia topaz") is sold as a variety of topaz to increase the value of the quartz. Buyer beware!

Name:	**Tourmaline**			
Chem:	$\mathbf{(Li,Na,Ca)(Fe,Mg,Mn,Al)_3(Al,Fe)_6(BO_3)_3Si_6O_{18}(OH,F)_4}$ AluminumBoroSilicate (wide variety of substitutions)			
Crystal:	Hexagonal (long prismatic, striated, with a rounded triangular cross section)			
Color:	black(schorl), brown(dravite), blue(indicolite), pink(rubellite),green, yellow, orange, multicolor, clear (rare)			
Refrac. Index:	1.616 - 1.652	**Birefraction:**	0.040	
Hardness:	7 - 7.5	**Spec. Grav.:**	3.0 - 3.3	
Fracture:	uneven	**Cleavage:**	none	
Environment:	Found in igneous and metamorphic rocks, in shists, pegmatites, and hydrothermal replacement deposits			
Association:	lepidolite, microcline, spodumene, andalusite, biotite, quartz, cassiterite, molybdenite			
Locals:	| Brazil | Calif., Maine, USA | Sri Lanka | Italy | USSR |			
Misc:	The name apparently comes from the Sinhalese word "Turamali" which was given to mixtures of unidentified gem gravels in Ceylon (now Sri Lanka). Insoluble in acids. Strong pyroelectric, and piezoelectric properties. This pressure/electric relationship is used in some high pressure gauges.			
Gem info:	Tourmalines come in just about every color in the rainbow. Some of the colors have unique jewelry related names. Pink to Red tourmaline is known as rubellite, and the color is probably from manganese. It is one of the most valuable of the tourmalines when the colors are dark and rich. Large flawless stones are rare, as the pink variety tends to have more flaws. Greens - there are two distinct families of green tourmaline, one contains trace amounts of chromium (and coincidentally is called Chrome Tourmaline). It has a high value. Other shades of green may run from light green, to dark olive green and they tend to have less value than the chrome, blue or pinks. Blue - blue tourmaline is known as indicolite and is highly prized. The best stones are pure blue without hints of green or gray. It tends to be of similar color to dark blue topaz. A new variety of light and very lively blue was			

discovered in Parabia, Brazil, and has achieved the highest prices paid for tourmaline. Analysis of this material show trace amounts of gold in the structure. Blue stones can be found that are large and flawless. They do not suffer from the poor structure found in rubellite.

Yellow and orange tourmaline maintains intermediate value as long as it does not move into the brown region. Clean yellow and bright orange stones are sought after by collectors and find their way into a small amount of commercial jewelry.

Brown and orange-brown stones are quite common and are not highly valued.

There is a special variety of tourmaline that shows a pink/red interior, and is surrounded by a green exterior "rind". It is called "watermelon" tourmaline, and is often cut and polished flat across a crystal face. It is sometimes cabbed, and even faceted.

Some faceted tourmalines show color changes from top to bottom. Most often these stones are cut into long, rectangular shapes and may display two or more color changes down their long axis. They are usually called bi-colored or tri-colored stones.

Finally, some pinks, yellows, and greens, may show chatoyance, and produce cats-eye cabochons.

Name:	**Turquoise**	
Chem:	**$CuAl_6(PO_4)_4(OH)_8 * 5H_2O$** Hydrous copper aluminum phosphate	
Crystal:	Triclinic (crystals are rare, usually compact or massive blocks)	
Color:	sky blue, bluish-green, pale green	

Refrac. Index:	1.61 - 1.65	**Birefraction:**	0.04
Hardness:	5 - 6	**Spec. Grav.:**	2.60 - 2.80
Fracture:	conchoidal	**Cleavage:**	none
Environment:	a secondary mineral in the alteration zone in hydrothermal replacement deposits		
Association:	quartz, pyrite, chalcopyrite, apatite		
Locals:	| Iran | Az., Nv., N.M., USA | Egypt | Afghanistan |		
Misc:	The name comes from the French "turquoise", which means "Turkey" as in the original great localities in Persia (today Iran). Soluble in hot HCl		
Gem info:	Turquoise has been used and coveted since before 4000 BC. It can be pure in color or may contain secondary minerals or even matrix. If the matrix forms a pattern of interlocking polygons it is sometimes called "spider-web" turquoise. The associate minerals often make the original local easy to pin-point. The very best material still comes from Iran today. It has a one of the highest values of opaque gemstones and is second only to a few varieties of jade and the highest quality lapis. It was used in much of the early American Indian jewelry and was often mixed with red-coral, pink-coral, or malachite. Today it is often found in intarsia with lapis, sugilite, and even opal. A chalky variety is sometimes pressure treated with a plastic-polymer to make "stabilized" turquoise. It is worth far less than the non-stabilized material.		

Made-made stones can be divided into two major categories, imitations and true synthetics.

Imitations: are artificial materials which look like a real stone, but have entirely different chemical compositions. Colored glass was used to mimic many real stones in the past, and is an imitation of everything except obsidian. (It could be considered to be a synthetic obsidian.)

Plastic, glass, paste, natural organics, and compressed powders have been used to create simulants (imitation gemstones). There is another category which might lie between imitation and synthetic, and that is composite stones.

A composite might be a quartz bottom and top, sandwiching a thin piece of colored glass or even a thin mineral sample. A faceted top and bottom will reflect the thin slice of color throughout the entire stone, and the only way to easily see it is to look "edge-on" right at the joint.

Cubic Zirconia: is used to simulate a diamond and the composition ZrO2 is not a natural occurring chemical structure. It has hardness of about 8.5, and a specific gravity between 5.65 - 5.95 (gm/cm3). It is very inexpensive and has a dispersion slightly greater than diamond, and this produces an abundance of color play. It is available in a variety of colors. Sample 1 (multicolors) - Sample 2(clear). A radio-frequency "skull crucible" system is used to melt and recrystallize the CZ. Due to its extremely high melting point, (2750 C or 4604 F), it was not synthesized early. The melting zirconia powder actually creates the sides of its own container during its formation.

Strontium Titanate: another simulant with a man-made chemical structure $SrTiO_3$, but with a much lower hardness, 5.5. It has a much higher dispersion than diamond (0.19), and thus far more color-play. It was produced in some quantity in the mid 1950's, but has been replace by CZ with it's higher hardness, and better diamond matching dispersion. It's known as "Fabulite" in the jewelry industry.

Fiberlite: this is actually fused fiber-optic glass that can be colored during the fusion process, and when cut into cabochons forms a strong catseye. The material is fibrous glass so is actually amorphous. Sample 1 (3 stones) - Closeups of structure, 2 closeup near the catseye (parallel fibers), 3 edge of yellow rough showing linear fibers on the side and bundles at the top, and 4

showing the bundles with fused glass in-between.

Slocum Stone: is another imitation. It appears to be a type of glass, and is used to imitate opal. It is harder and more heat resistant. There are samples and photos in the gemstone section under opal.

Synthetics: have the composition of a known mineral, but do not necessarily match the composition of the gemstone it is to mimic. They may be created by mimicking the natural process, by recrystallizing natural stones, or through an entirely new man-made technology. They share the same chemical structure, and general physical properties with their natural counter parts.

Chatham Ruby: this ruby is very hard to distinguish from natural ruby. It is created from a melt - recrystallization process. It has the same corundum (Al_2O_3) chemical structure, and shares the same general types of flaws. Sample 1.

Verneuilli Process Corundum: another variety of corundum which is produced by a high temperature fusion of pure aluminum oxide with small amounts of impurities added to provide color. The red rubies created via this process tend to be too pure, flawless, and lack the "ruby-red" color found in the natural stone. They do have the right composition and hardness. The material forms what is known as a "boule", cylindrical shape, tapered at one end.

The Line Company adapted this process to create synthetic star sapphires. They added a small amount of TiO_2 (rutile) during the creation phase.

Another similar process, known as the Czochralsky process, is also used to make synthetic corundum. It differs in the way the boule is drawn and twisted as it is removed from the flame zone. It can produce larger diameter boules.

Synthetic Spinel: this is produced by the same process as the corundum, and was originally discovered while trying to use magnesium oxide as a stabilizer for a corundum run. The synthetic material can be made with ratios of aluminum oxide to magnesium oxide of 1:1, 2:1 or even as high as 4:1. It forms very pure colors and flawless gems. It is used to create a specific material that imitates alexandrite with a moderate color change.

Name:	**Zircon**		
Chem:	**$ZrSiO_3$** Zirconium silicate		
Crystal:	tetragonal (often short four-sided prisms with pyramidal ends)		
Color:	brown, red, blue, yellow, green, clear, violet		
Refrac. Index:	1.777 - 1.987	**Birefraction:**	0.039
Hardness:	6.5 - 7.5	**Spec. Grav.:**	4.6 - 4.71
Fracture:	conchoidal	**Cleavage:**	imperfect
Environment:	found in both igneous and metamorphic rocks		
Association:	orthoclase, biotite, acmite		
Locals:	| Australia | Fl., Maine, Co., N.J., USA | Sri Lanka | Urals | Canada |		
Misc:	The name comes from the Persian "zargun", meaning "gold-colored". Is mined for its zirconium and hafnium content.		
Gem info:	The majority of rough is brown or yellow-brown in color, and is often heat treated producing blue zircon of clear zircon. The blue, sometimes called "starlite" is popular in jewelry, although quite brittle, it has a high dispersion and produces brilliant cut stones with sparkle similar to diamond. The yellow-red to red-brown variety is sometimes called "hyacinth". The rarest form is the green, and is the most demand by collectors. Yellow , brown, and clear stones are least valuable. Blue, clear red and bright green are the most prized. They are still well below the top colored gems, but in the same area as medium priced topaz, and beryls.		