MIDTERM STUDY GUIDE - TOPIC MATERIAL COVERING FIRST HALF OF COURSE

INTRODUCTION

1. **Scientific method** – observations, hypotheses, theories etc.

- **a.** uniformitarianism versus catastrophism and their applicability to scientific method

2. **Earth history overview**

a. The **Nebular Hypothesis**: The Earth and most of the Solar System condensed from a gas cloud. The Earth's major internal layers (described below) probably formed very early in the Earth's history, while it was still mostly molten.
b. **Differentiation event** of earth's major layers
c. **Origin of the Moon** - Impact theory
d. Origin of the ocean - volcanic out-gassing and comet impacts
e. **Age of Earth**: 4.5 - 4.6 billion years old; ~3.8 Ba oldest rocks in the crust (water); 3.5 Ba - 800 Ma-old rock showing little life but microbes and algae until 570 Ma (million years ago), when many forms of life rapidly evolve (e.g., trilobites)
f. See my lecture notes for a brief list of important events in earth history (its on the class website)

PLATE TECTONICS

1. **Earth structure**

a. Earth's compositional layering; (see handout)

- **i.** Inner and outer core; mostly iron plus some nickel
- **ii.** Mantle; dense rock (iron and magnesium rich silicate minerals; mostly olivine
- **iii.** Crust: 'the cream that floated to the surface,' low-density silicate minerals. Be able to compare and contrast continental and oceanic crust

b. Earth's mechanical layering: (see handout)

- **i.** Solid inner core
- **ii.** Liquid outer core
- **iii.** Mesosphere – moderately strong lower mantle
- **iv.** Asthenosphere – relatively weak, plastic upper mantle
- **v.** Lithosphere (rigid outer shell!). ~100 km thick (~60 miles).

2. Plate tectonics overview

a. Plate Tectonics basics

- **i.** Pre-plate tectonic ideas: Continental Drift hypothesis - Wegener
- **ii.** Earth has a strong, rigid outer silicate shell that is broken into 11 or 12 major lithospheric plates that move relative to each other.
- **iii.** Lithosphere made up of crust and underlying uppermost part of mantle.
- **iv.** Lithosphere floats on weak, partially molten asthenosphere layer.
- **v.** Know the 3 types of plate boundaries and the major things that happen at each boundary type, including the major tectonic processes that occur

there. Know an example of each type of plate boundary, and associated volcano(s), magma types, earthquake faults, etc.
vi. Continental and Island arcs, mid-ocean ridges, deep sea trenches, etc.
vii. Movement of plates is driven by sinking of oceanic lithosphere at subduction zones, convection in the mantle/asthenosphere; interior of the Earth is hot
viii. Plates move centimeters per year, tens of kilometers per million years
ix. Hot spots – stationary spots of intense volcanic activity; plates move over them. Hawaii
x. Plate tectonics is a unifying theory of geology
xi. Plate tectonics explains many things, such as location of most earthquakes and volcanoes; areas ancient life forms inhabited; outlines of continents; age of seafloor; locations of mountains
xii. Check textbook for a list of important aspects of each type of plate boundary. Know this stuff (earthquakes, volcanic arcs, sea floor age, etc.)
xiii. Check textbook for side-view sketches of a convergent and a divergent plate boundary – be able to correctly visualize these cross-sections.

b. Plate Tectonics details
i. Driving forces (slab pull, ridge push, mantle convection)
ii. Locations of plate boundaries (carefully study plate map in textbook)
iii. Plate boundaries on the west coast of North America
iv. San Andreas fault, Juan de Fuca plate, Cascade volcanic arc, sea floor spreading in the Gulf of California
v. Mid – ocean ridges; where they are, why the exist, etc.
vi. Active and passive continental margins

c. Evidence for the Plate Tectonic Theory
i. Continent-based evidence - Like what Wegner collected
ii. Ocean-based evidence

MINERALS

1. Atoms - the basic unit of matter; comprising
a. nucleus
i. protons and neutrons – have mass, protons have (+) charge, neutrons no charge.
b. orbiting electrons –
i. same number as protons in an atom if it is in its neutral or base state (which atoms often aren't in).
ii. Negative charge of 1 – equal but opposite to a proton's charge, almost no mass.
iii. in shells, shells want to be full (e.g. 2 electrons in 1st and 8 in 2nd and 3rd shells)
c. number of protons in an atom determines what element it is.

d. in their neutral or base state atoms have the same number of electrons as protons and consequently no net charge
e. the opposite charges of electrons and protons keeps electrons in orbit around the nucleus of an atom

2. **Elements**
   a. all matter can be broken down into the few elements that it is made from. Put another way, the multitude of types of substances that exist are all made out of combinations of the relatively few elements that exist, just as a multitude of meals can be made from various combinations of the relatively few ingredients in your cupboard.
   b. an element consists of all atoms with the same number of protons. For example, the element carbon comprises all atoms with 6 protons. The number of neutrons and/or electrons can vary, and an atom is still carbon if it has 6 protons. [note that your book is slightly different and more complicated on this definition].
   c. major, most common elements in the Earth's crust? - **Oxygen, Silicon**, Aluminum, Iron, Calcium, Sodium, Potassium, Magnesium. Oxygen makes up nearly half the weight of the Earth's crust, and silicon makes up about a quarter - know that O and Si together make up about 75% of the weight of the Earth's crust. Know the names of the other common elements.
   d. isotopes: an isotope of an element is all atoms of an element that have the same number of neutrons. Carbon has 3 relatively common isotopes: one with 6 neutrons, one with 7, and one with 8.
   e. The two most abundant elements in the Earth's crust are oxygen and silicon. Oxygen makes up nearly half the weight of the Earth's crust, and silicon makes up about a quarter.

3. **Bonding** - how atoms attach to each other
   a. occurs because electrons of neighboring atoms interact with each other this happens because the electron shells around the atoms 'want' to be full – they are in a lower energy state when they are full.
   b. 4 types of bonds (we mostly talked of just 2) – covalent and ionic most important in rocks.
      i. Ionic – and electron is transferred from one atom to another; the atoms then each have opposite charges that holds them together. Medium strong bond; NaCl (table salt) is a prime example of this type of bonding. The atoms exchange electron(s) so that their outermost shells will be full.
      ii. Covalent – electron sharing. In a covalent bond, neighboring atoms share one or more electrons and form a hybrid shell that is 'full' of electrons. This makes the strongest type of bond. Silicon and oxygen form this type of bond (and Si and O are the most abundant elements in the Earth's crust) Carbon forms this type of bond in diamonds.

iii. Van der Waals. A weak electrostatic interaction (i.e., (+) attracts (-)). Occurs between sheets of atoms – sometimes atoms strongly bond into sheets and the positioning of the electrons in the bonds creates a weak (+) charge on one side of the sheet (i.e., the top) and a (-) charge on the other side. Consequently, sheets are attracted to each other, but not particularly strongly. This bond is important in graphite and some clay-type minerals. Its weakness in graphite is readily apparent when you drag a pencil across a paper.

iv. Metallic Bonds. In some metals (e.g., gold, silver, copper etc) outermost electrons are far from nucleus and only weakly held, so can wander a lot. Sharing of electrons and charge differences between atoms hold them fairly weakly together, but notably the mobility of electrons gives metals many of their special properties: 1) ductility (non-rigid bonds); 2) electrical conductivity (movement of electrons); 3) thermal conductivity (vibrations of atoms).

4. Crystals - regular, repeating, geometric arrangement of one or more types of atoms that are bonded together. Amorphous solid materials with randomly arranged atoms *are called* ***amorphous solids*** *and are not crystalline; glass is an example of such a substance*. We looked at halite (NaCl)'s cubic structure. The pattern in which atoms are arranged in a crystal is called the **crystal lattice**.

5. Minerals - naturally occurring, inorganic, crystalline solids with restricted, definable chemical compositions and characteristic physical properties

a. the physical properties? (color, luster, hardness, density, cleavage etc.)

b. definable, restricted chemical composition – composition of a mineral can vary within a restricted range

c. major mineral groups - silicates, carbonates, halides, sulfides, sulfates, oxides, native elements

d. silicates are most abundant in Earth and the crust; most important/abundant types of silicate minerals:

i. ferromagnesian - **olivine, pyroxene, amphibole, biotite** (in order of decreasing amount of Fe&Mg relative to Si). Know these minerals and be able to list them in order of amount of Fe&Mg relative to Si in them.

ii. non-ferromagnesian - **quartz, potassium feldspars, plagioclase feldspars, muscovite** (also clay)

iii. crust and mantle are made mostly of silicate minerals, because silicon and oxygen are the most abundant elements in the crust and they form a strong covalent bond.

iv. silicate tetrahedron – covalently bonded. Si + O form a tetrahedron of four O atoms around each Si atom (see picture in book). **The silicate tetrahedron is the basic building block of most of the Earth's crust and mantle!** Other elements generally attach to the silicon tetrahedron with ionic bonds.

MINERAL RESOURCES

1. Know difference between **Resource** and **Reserve**

2. Know difference between **a Renewable** resource and a **Nonrenewable** resource

3. Major Types of Mineral Resources

- **a.** Metals
  - **i.** Base metals
  - **ii.** Precious metals
  - **iii.** Know the most important specific metals by name for both groups
- **b.** Industrial Minerals
  - **i.** Electronics industries
  - **ii.** Chemical industries
  - **iii.** Manufacturing industries
  - **iv.** Know most important specific minerals by name for each group
- **c.** Construction Minerals
  - **i.** Buildings, bridges, dams, roads, etc.
  - **ii.** Know most important specific minerals for each type of application
- **d.** Jewelry
  - **i.** Precious gems and semi-precious gems
  - **ii.** Know most important gems by name
- **e.** Energy Minerals and non-minerals
  - **i.** Fissionable elements
  - **ii.** Fossil Fuels
  - **ii.** Know most important specific minerals by name for each group

4. Geologic origin for the major types of mineral resources

- **a.** Magmatic
- **b.** Hydrothermal
- **c.** Metamorphic
- **d.** Sedimentary

5. Methods for locating, extracting, and processing the major minerals resources

6. Specific applications and uses for the various major minerals resources

IGNEOUS ROCKS

1. Igneous Rocks and Igneous Rock Processes – we covered igneous rock types in the first midterm, and pick up with volcanoes for the second midterm

- **a. Minerals** - naturally occurring, inorganic, crystalline solids with restricted, definable chemical compositions and characteristic physical properties
  - **i.** the physical properties? (color, luster, hardness, density, cleavage etc.)
  - **ii.** definable, restricted chemical composition – composition of a mineral can vary within a restricted range
  - **iii.** major mineral groups - silicates, carbonates, halides, sulfides, sulfates, oxides, native elements

iv. Silicates are most abundant in Earth and the crust; most important/abundant types of silicate minerals:

1) ferromagnesian - **olivine, pyroxene, amphibole, biotite** (in order of decreasing amount of Fe&Mg relative to Si). Know these minerals and be able to list them in order of amount of Fe&Mg relative to Si in them.

2) non-ferromagnesian - **quartz, potassium feldspars, plagioclase feldspars, muscovite** (also clay)

3) crust and mantle are made mostly of silicate minerals, because silicon and oxygen are the most abundant elements in the crust and they form a strong covalent bond.

4) silicate tetrahedron – covalently bonded. Si + O form a tetrahedron of four O atoms around each Si atom (see picture in book). **The silicate tetrahedron is the basic building block of most of the Earth's crust and mantle!** Other elements generally attach to the silicon tetrahedron with ionic bonds.

v. Igneous rock-forming minerals form in a crystallizing magma according to the **Bowens Reaction Series**

1) Composition/temperature-dependent crystal-forming process

2) Continuous Series

a) High temperature Ca-rich plagioclase → low temperature Na-rich plagioclase

b) Continuous spectrum from 100% Ca plagioclase to 100% Na plagioclase with all intermediate compositions (example 50/50) in between.

3) Discontinuous Series

a) Olivine (high temp end) → pyroxene → amphibole → biotite (low temp end)

b) Discontinuous generation of different minerals by either 1) new crystals directly from melt and/or 2) alteration older high-temp minerals to lower-temp minerals by reaction with melt.

4) End Series:

a) Potassium feldspar + Quartz + Muscovite

b) Potassium feldspar forms if melt is potassium rich

c) Quartz only forms in the presence of excess silica

d) Muscovite only forms in presence of excess aluminum

b. Rocks and the Rock Cycle

i. Know the 3 primary types of rocks and the basis on which the three types are distinguished.

1) Igneous; 2) Sedimentary; Metamorphic

ii. Know what the 'Rock cycle' is.

iii. All rocks are solid aggregates of one or more minerals.

iv. There are many (1000's) kinds of minerals, but really only a few make up most rocks, especially igneous (the few silicates listed above).

v. There are three kinds of rocks: igneous, sedimentary and metamorphic; the most primitive being igneous

vi. Igneous rocks are rocks that have formed directly by cooling and crystallization (solidification into crystals) of molten rock (magma or lava).

1) Magma (molten rock) is about 1800oF (1000oC) to 2400oF (1300oC). Pretty darn hot, but not unbelievably hot.

2) Felsic magma is at the low end of the range and mafic magma at the high end.

c. Types of Igneous Rocks

i. There are 2 basic ways to categorize igneous rocks:

1) By texture, which ranges from pegmatitic to glassy

a) Super coarse-grained, or *pegmatitic*; and coarse-grained or *phaneritic* (both cooled very slow, probably deep underground = intrusive or plutonic)

b) Fine-grained or *aphanitic* (cooled very fast, probably at or near the surface = extrusive or volcanic)

c) No-grained or *glassy* (cooled super fast, probably at the surface = extrusive or volcanic)

d) Mixed-grained or *porphyritic* (Initially cooled slow, then the remaining magma cooled fast, probably at or near the surface = intrusive-extrusive or plutonic-volcanic)

e) Clastic-grained or *fragmental* (cooled very fast in the air immediately after being erupted out of a volcano, then eventually falls to ground as volcano-clastic debris and piles up (extrusive-volcanic-sedimentary)

2) By composition, which ranges from *felsic* (silicon & aluminum & sodium & potassium -rich) to *mafic* (iron & magnesium - rich/ silicon-poor), with *intermediate* in between. Ultramafic are ultra rich in iron and magnesium (mantle-like).

ii. Main types of igneous rocks (granite, rhyolite, basalt, etc.) are **named based on both composition and texture**.

iii. Some igneous rocks are named based primarily on special textural traits (not just fine or coarse – grained texture; see 1e) above):

1) obsidian (glassy)
2) pumice (vesicular)
3) scoria (vesicular
4) lapilli (pyroclastic)
5) tuff (pyroclastic)

iv. Rock ID: We can tell a rock's composition from the minerals present in it: felsic (rhyolite & granite) through intermediate (andesite & diorite) to mafic (basalt and gabbro). See figures in your textbook.

v. Most common rock-forming minerals: Know 9 minerals that are most common in igneous rocks and be able to list the ferromagnesian ones in order of decreasing iron and magnesium (see above). Know that Calcium plagioclase goes with lots of iron and magnesium and sodium plagioclase goes with little magnesium and iron (but lots of silicon). Quartz only forms in rocks that have excess silicon; that is, Si is left over after all the Fe, Mg, Al, K, Ca and Na have been taken into the other silicate minerals.

d. Magma formation at mid-ocean ridges and hotspots

i. Melting mid ocean ridges and hotspots

1) Magma forms by **Decompression melting**. During the process of decompression melting, hot mantle rock rises towards surface. As it moves upwards it remains relatively hot but experiences greatly reduced pressure. Reduction in pressure causes it to partially melt (< 10% of rock melts).

2) Mafic magma is formed because ultramafic mantle rock is partially melted.

a. **Partial melting**: When rock melts, especially mantle rock, the resulting magma is more felsic than the original rock that melted. For example, when ultramafic mantle rock partially melts, a mafic magma is produced. When a mafic rock is partially melted, an intermediate magma is formed. etc.

ii. Volcanism at mid ocean ridges and hotspots

1) The mafic magma at MOR's and hot spots are relatively hot, low viscosity, and low in dissolved gases.

2) Consequently, volcanism tends to be **non-explosive** – although escaping gases can cause dramatic fountaining of lava.

3) Large, shallowly sloped **shield volcanoes** can result at hot spots – for example, Mauna Loa on Hawaii.

4) Decompression melting and basaltic volcanism can also result in **flood basalts** issuing from fissures. The **Columbia River basalts** are an example.

iii. Intrusive igneous activity at mid ocean ridges and hotspots

1) The lower portions of all oceanic crust are made of gabbro, which is phaneritic mafic igneous rock (equivalent to basalt, but cooled slowly). Presumably there is gabbro under Hawaii, but it has not been seen and is unlikely that the overlying oceanic crust and volcanoes will ever be eroded away so that we can see it.

e. Magma formation at subduction zones

i. Melting at subduction zones

1) Melting at subduction zones is caused by **water fluxing**. Tremendous amounts of seawater are carried downwards within the subducting oceanic crustal slab at deep sea trenches. This water is eventually released into the hot mantle rock above the subducting lithosphere/crust (somewhere around 100 to 120 kilometer depths) due to increasing temperatures (dewatering effect). In the initial stages of the process of water fluxing, the released slab water causes a fluxing effect, which lowers the local melting temperature of the surrounding mantle rock, thereby causing the mantle rock to partially melt. Adding water to hot rock is analogous to adding salt to ice.

2) Intermediate composition magma is formed. Initially, mafic magma is probably formed, but the magma that solidifies into plutons (and whole batholiths) in the overriding crust, and reaches the surface to form volcanoes is, on average, intermediate in composition. The originally mafic magma is made more felsic by **differentiation** and **assimilation**.

a) Differentiation occurs when the magma first begins to become solid, mafic minerals (rich in Fe (iron), Mg (magnesium) and Ca (calcium)) such as olivine and pyroxene crystallize, sink, and are separated from the magma (recall from **Bowen's Reaction Series** that mafic minerals have higher melting temperatures than felsic minerals). The removal of mafic minerals from the magma leaves it depleted in those elements and enriched in Si (silicon).

b) Assimilation occurs when felsic/silicic rock from the crust the mantle-derived magma is rising through is melted and incorporated into the magma. This makes the magma less mafic.

f. Volcanism – General Information

i. Lava - relation between composition, temperature, viscosity, and gasses

1) Basaltic is hotter, lower viscosity, flows faster, less explosive, forms mostly at divergent boundaries, hot spots. Lots gets erupted each year (on average), since much of all new oceanic crust is made of it, as are hot spot islands which are really big volcanoes.

2) **Intermediate composition** magma is typically volatile-rich and explosive, and forms mostly at subduction zones. There are several ways to form an intermediate. Initially, mafic magma is probably formed, but the magma that solidifies into plutons (and whole batholiths) at the base of the overriding crust, will get partially melted to form andesitic melts that eventually rise and reaches the surface to form stratovolcanoes. The originally mafic magma is made more felsic by differentiation and assimilation.

3) Rhyolite is cooler, much more viscous (mostly because it's cooler), barely flows at all, can be very explosive. Intermediate is in between, generally doesn't flow all that well.

ii. Volatiles. Magmas have variable amounts of volatiles (dissolved gases), especially H2O and CO2, dissolved in it, which need to escape when the magma erupts as lava and pressure is released. Relate this to viscosity, fountaining, big explosions like Mt. St. Helens etc. Exsolving gases from a crystallizing magma creates vesicles in lava.

1) Origin of the dissolved volatiles are from the mantle and subducting slab.

iii. Volcano Types

1) Shield - basaltic, layered, very big, hot spots, main and side vents are common, see book. Hawaii.

2) Composite/Strato Volcanoes - andesitic to rhyolitic, smaller, alternating layers of lava and pyroclastic flows, explosive (thick, viscous lava), volcanic arcs like the Cascades and Andes.

3) Cinder cones

4) Volcanic plateaus - Basalt also sometimes comes out in huge quantities through fissures kilometers long to make '**flood basalts**,' such as the Columbia River Basalts (164,000km2 in area!)

iv. Volcanoes and Plate Tectonics

1) Most active volcanoes occur at plate boundaries.

2) Composite volcanoes form at convergent plate boundaries and are related to subduction (have a rough idea of a side view of a subduction zone with volcanoes over the subducting slab, plutons forming under the volcanoes).

a. Most composite volcanoes form along the "Ring of Fire" around the Pacific Rim

3) Most shield volcanoes form at hot spots.

a. Large, shallowly sloped **shield volcanoes** can result at hot spots – for example, Mauna Loa on Hawaii.

4) Lots of basaltic volcanism at divergent boundaries (mid-ocean ridges and continental rifts), but nearly all is undersea.

v. Other types of volcanic features see book, PP, and lecture notes

1) Calderas .
2) Volcanic domes
3) Volcanic necks
4) Fissure eruptions
5) Columnar jointing

vi. Volcano case studies

1) Mt. St. Helens (see textbook; erupted about 1 to 2 km3 or 0.24 to .5 cubic miles of ash)

2) Long Valley Caldera and Mammoth Mtn. (see handout on class website if your notes are incomplete)

3) Yellowstone

a) 2 million years ago erupted 600 cubic miles (2500 km3) of ash and formed a large caldera that is hard to see today due to erosion and more recent volcanic activity

b) 630,000 years ago erupted 240 (1000 km3) cubic miles of ash and formed a large caldera that is fairly readily visible today

c) There have been numerous smaller eruptions in addition to the huge "supervolcano" events listed above. Still active today – magma is present a few miles beneath the park!

2. Formation of Magma and Intrusions at Edges of Continents

a) Large volumes of magma cool and solidify within the edges of active margin continents beneath the continental volcanic arcs in association with subduction zones.

b) Most or all of the true, large **batholiths** in the world formed over subduction zones. The batholiths are made of many individual **plutons** that were emplaced over the life of the subduction zone (tens of millions of years), and they are intermediate to felsic in composition on average.

c. Intrusive (igneous) Rock Bodies

i. **Plutons** - all encompassing term for intrusive rock bodies, which are essentially crystallized magma chambers.

ii. **dikes**, **sills**, **laccoliths**, **volcanic necks**, **batholiths** (these are in the book; be able to name them from a picture).

1) Know that **dikes** cut pre-existing layers whereas **sills** parallel them, but that both formed by magma flowing into a (big) crack. It is not necessarily true that dikes are vertical and sill are horizontal, because the country rock layering is not necessarily horizontal.

2) Know that **laccoliths** are 'domed -up'(mushroom-shaped) sills.

3) Know approximate time required for formation of intrusions.

a) Batholiths – they comprise many individual plutons, consequently take millions to tens of millions of years to form, and mostly form over subduction zones (beneath the chains of volcanoes that form over subduction zones).

b) Sierra Nevada and Peninsular Ranges batholiths are nearby and well-studied example. These batholiths formed over tens of millions of years.

iv. Intrusion Emplacement - **how does the magma rise thru the crust?**

1) The basic driving force is **buoyancy** - the magma is less dense than the surrounding rock because it is hotter; less dense material wants to rise like a hot air balloon. Think of the lava lamp.

2) Magma can rise though heated, softened, "weak" lower to middle crust by means of **diapiric** movement - much like how "lava blobs" in a lava lamp rise through the surrounding fluid.

3) Magma can rise though relatively cold, brittle, "strong" upper crust by means of **fault-controlled** movement - squeezing its way up through "weak" fault zones. A classic example are "sheeted dikes"

SEDIMENTARY ROCKS

1. **Sedimentary Rocks -** The major sedimentary processes to know and understand are **weathering, erosion, transport, deposition** and **lithification**.

a. **Weathering** - minerals stable deep in the Earth are not necessarily stable at the surface. They break down in place - which is weathering

i. Mechanical - freeze-thaw, organic, abrasion, heating+cooling

ii. Chemical - solution (getting fully dissolved and then can be carried away in the water), and chemical reactions to form new minerals that are more stable at the surface of the Earth (clays and rust-like minerals are common products).

1) Oxidation (e.g., rusting) is another common type of chemical weathering that involves chemical reactions of this type. Note also that both solution and the formation of new minerals can result essentially simultaneously.

2) Limestone is very susceptible to being dissolved, whereas quartz is not.

3) Understand why water is so powerful at dissolving substances, especially ionically-bonded substances.

iii. Rocks weather at different rates, which gives rise to lots of neat landforms. Many neat patterns in the layered sedimentary rocks throughout southern Utah result from this.

b. **Erosion** - removal and transport of weathered rock

i. water, wind, glaciers. **Rivers** are by far biggest agent.

ii. when you have weathering but little or no erosion, coupled with organic activity you get **soil**. **Soil** can also form where sediments have been deposited, say by floods along rivers. **So soils are weathered rock + organic material**. Soils take time to form, and can be completely and indefinitely lost when vegetation is removed, as in many rain forests.

iii. **Soil**: know what it is, how it forms.

c. **Types of Sedimentary rocks**:

i. **Detrital** (know the various types of detrital rocks)

ii. **Bio-chemical** (know the various types of bio-chemical rocks, such as coal, chert, limestone, evaporites)

d. **Transportation**.

i. Detrital sediments (bits of rock fragments, like pieces of sand) are transported by streams, wind, glaciers and waves.

1) Weathering continues during transportation, and detritus is rounded (amount of rounding of detritus can indicate the transportation distance).

2) Wind and streams have a bed load, suspended load and a dissolved load.

ii. Dissolved rock is transported primarily by water, although CO2 (a constituent of calcite in limestone and important to global warming) is transported by wind.

e. Sedimentation/Deposition. Need to talk separately about detrital and chemical sediments.

i. Detrital material size

1) Comes in several **sizes - gravel, sand, silt, clay** (see book).

2) When detrital material (ground up rock) is **deposited**, it forms layers of **sediment** (its not rock yet!).

3) Fine material is deposited in low **energy** environments (e.g. quite water like out in the ocean or in a bay,

4) Coarse material (sand, or especially gravel) gets deposited in energetic water (fast river or creek, right on a beach).

5) Imagine shaking up a jug of water mixed with a several cups of sediment of various sizes --- how would the different sized materials settle out, in terms of layering? Important thing here is the grain size of sediment or a sedimentary rock tells you a LOT about where it was deposited (the **depositional environment**).

5) Sorting also results from the deposition environment; beach sands tend to be very well sorted because they are subjected for a long time to a particular amount of water '**energy'** (energy is sort of like turbulence).

6) Sorting and **rounding** together are the important detrital sedimentary **textures**

7) Detrital structures - geometric features in the rock. They tell you about how the rock formed: **cross bedding, ripples, mudcracks, etc.** see book, notes.

ii. Chemical material mostly forms **calcite** ($CaCO_3$), **dolomite** ($CaMg(CO_3)_2$, **gypsum**, and good ol' **salt** (NaCl). When water - especially water that was 'salty' to begin with, like seawater - evaporates, it leaves a bunch of bio**chemical sediments** (mostly gypsum and salt) behind.

iii. Also must consider **organic** or **biochemical sediments**, such as accumulations of calcite shells which form **coquina**, leaves and other vegetation which make **peat** (can become **coal** with proper heating and compaction), or silica (SiO_2) shells which can form **chert**.

iv. Depositional Environments – 1) examples are alluvial fans, lakes, rivers, oceans (beach, near shore, reef/offshore, deep sea), glacial, sand dunes, evaporite basins (where a lake or sea evaporates, like the salt flats) 2) Determining the environment that sediment was deposited in is like detective work; depositional environments are generally identifiable by **sedimentary structures** and features in a sedimentary rock.

a) features include chemical vs detrital sediment, grain size + sorting + rounding (for detrital).

b) structures include mudcracks, ripples and cross-beds.

c) An example: the very fine grained, very will sorted sandstones with very thick (3 to maybe 20+ meters) cross-beds (and a few dinosaur footprints) in southern Utah are mostly ancient sand dunes.

f. **Lithification** - transformation of sediment into rock by compaction and cementation. Fundamental driving force here is the burial of the sediment under more and more layers of sediment. For example, there are maybe 4km of sediments in the offshore basins of southern California, so the sediments at the bottom are under a lot of pressure (think how heavy a 2.5 mile tall pile of dirt must be!!), and they are a bit warm, maybe 80oC.

i. Compaction - sediment typically is 15 to 90% pore space (voids in the rock, usually filled with water or air). When the sediment gets buried under layers of more sed., the weight compacts the sediment,

usually to where it has 5 to 15% pore space. Remember that there is a lot of weight on a rock that is buried a mile or two deep in the Earth.
ii. Cementation - basically the sediment grains get glued together. The cement minerals commonly are calcite, silica or clay. The glue is either material from the sed. grains that gets dissolved off the sharp tip of a sed. grain and precipitates next to the sharp tip, or its material that is carried by water flowing through the rock (say water getting squeezed out of sediments buried even deeper).

METAMORPHIC ROCKS

1. Define Metamorphic Rock - Igneous or sedimentary rock modified by heat and pressure in the solid state; a metamorphic rock has **NOT** melted during the metamorphic process.

2. **Four major agents of change**: Heat, pressure, fluids, and stresses.

i. Temperature in the crust increases about 20 ^oC to 25^oC with each kilometer of depth. This is called the *geothermal gradient*. Another source of elevated heat is from close proximity to magma intrusions

ii. Pressure in the crust increases by about 250 bars per kilometer (one bar equals one atmosphere of pressure, which is about 15 psi or about one half the air pressure in a car tire). Another name is called lithostatic pressure. At 20 km depth, it is pretty hot and a rock feels a lot of pressure, which leads to chemical changes, like cooking something in an oven. Another name is called lithostatic pressure.

iii. Water-rich fluids flowing through deeply buried crustal rocks have the potential for altering the country rock, due to their chemically-reactive nature. The process of rocks undergoing hydrothermal alteration is called *metasomatism*.

iv. Deviatoric stresses in the crust occur due to tectonic forces such as compression and shear. Think vice-like forces. It's these anisotropic stresses that give metamorphic rocks their foliated textures.

3. Heat (temperature) and **pressure** in the Earth's crust cause rocks to be **metamorphosed**. In the Earth's crust, temperature increases about 25 ^oC per kilometer depth (equal to about 75 ^oF per mile). Pressure increases greatly with depth. Metamorphism happens within the crust (i.e., not deeper).

4. Heat and pressure modify rocks through 3 mechanisms -

i. recrystallization (grow bigger crystals; this happens when marble forms from limestone).

ii. neomorphism (make new minerals out of the pre-existing ones),

iii. metasomatism (composition of the rock changes, usually because gnarly water moves through and dissolves then removes or precipitates material; new minerals form). Many economically important ore deposits result from metasomatism.

5. Metamorphic Grade. Grade describes how much heat and pressure a metamorphic rock experienced. Grades are described as high, medium, and low.

i. Low grade means relatively low heat and pressure, whereas, high grade means relatively high heat and pressure.
ii. Low grade is about 200 ^{o}C to 300 ^{o}C. High grade is 500 ^{o}C and above, medium is in between. The same pre-existing rock can end up as a slate, phyllite, schist or even gneiss (listed from low to high grade) depending upon on how much heat and pressure it undergoes (with more heat, a slate becomes a phyllite; with yet more heat a phyllite becomes a schist). Know this sequence of rocks, in order of increasing grade. Note that these are foliated rocks typical of regional metamorphism (see below).

6. A metamorphic rock's **texture** tells you about how it formed. Textures are so important that metamorphic rocks are often named on the basis of their textures. Note that these textures are different from the types of textures that are found in sedimentary rocks.

a. **Foliation** - planar layering that you can see - 4 types
i. Slatey - platy microscopic minerals - very fined-grained clays and micas - lined up in very tight, thin planar layers. Lowest grade.
ii. Phyllitic - platy sub-microscopic minerals - fined-grained quartz and micas - lined up in tight, wavy, thin planar layers that have a sheen-like luster. It has a texture between that of slate and schist.
iii. Schistose - platy, macroscopic (medium to coarse-grained) minerals - like biotite and muscovite - are lined-up in wavy layers. Quartz is also a common mineral seen sandwiched between the mica layers
iv. The three above types of layering are **perpendicular to the direction of maximum squeezing** (flattening) that the rock enjoyed during metamorphism. The minerals become aligned because the squeezing rotates the platy minerals into that position, and because the minerals can more easily grow (recrystallization) in the directions of the least squeezing. Slates, phyllites and schists all have this type of texture.
v. Gneissic foliation - compositional layering, usually dark and light layers of hornblende/biotite and feldspar/quartz. Often enough, the layering has been folded. Highest grade.

b. Non-Foliated - massive, non-layered rock - 2 types
i. Hornfelsic - non-platy microscopic minerals - very fined-grained. Typically dark-colored - looks like basalt. Lower grade.
ii. Granofelsic - non-platy macroscopic minerals - medium to coarse-grained. Looks granite-like. Higher grade.

c. Metamorphic rock names - know all the major names
i. Foliated rocks
1) Slate, 2) Phyllite, 3) Schist, 4) Gneiss, 5) Migmatite
ii. Nonfoliated rocks
1) Marble, 2) Quartzite, 3) Hornfels, 4) Amphibolite

7. Metamorphic environments. Regional, contact, dynamic, and hydrothermal metamorphism.

8. Regional metamorphism occurs where a large (mountain range-sized volumes of rock gets buried deeply enough to get metamorphosed, then makes its way back to the surface for us to look at and get fired up about. This typically happens as a result of subduction and/or mountain building and leads to the formation of ***foliated*** rocks like slates, schists, gneisses etc. Regional metamorphism usually lasts a long time, since it takes time for rocks to get buried deeply then pushed back to the surface; consequently, large crystals may grow if the rock gets hot enough.

a. Regional metamorphism at subduction zones can be relatively **low temperature but high pressure (low T/P**), **high temperature but low pressure (high T/P**), or **high-Temperature and high-pressure**. In fact, belts of the first two types of regional metamorphism almost always form alongside each other at subduction zones. Rocks that get pushed downwards (subducted) with the subducting oceanic plate enjoy low T/P metamorphism because they go deep into the Earth (say 20km = 12 miles, or more) but stay relatively cool because the subducting plate is cool from being at the surface of the Earth. (Eventually the subducting plate gets heated by the surrounding crust/mantle, but that takes millions of years).

b. Under and along the volcanoes over the subduction zone, relatively high-T, low-P regional metamorphism happens. This is caused by the hot magma that moves up into the crust over the 10's of millions of years that the subduction and causes volcanism and plutonism.

c. Both the low T/P and high T/P rocks commonly are exposed at the surface by erosion, and they form two belts. The belts are called **PAIRED METAMORPHIC BELTS** and they record the presence of a subduction zone in the past. A nice example of such a pair exists in California; the pair tells us there was a subduction zone there for a long time. Very deep under mountains rocks undergo very high-grade metamorphism that is both **high-Temperature and high pressure**.

d. Know these three types of regional metamorphism and be able to place them on an illustration of a convergent plate boundary. See your textbook for illustrations.

9. Contact metamorphism occurs around intrusive igneous bodies, where the hot magma and its associated magmatic fluids cook the surrounding preexisting rock. This results in rather high-temperature, low pressure, quick metamorphism.

a. This cooking along a pluton is a relatively local effect that usually is confined to within to hundreds of yards of an individual pluton. The resulting rocks usually are fine grained and non-foliated because contact metamorphic event doesn't provide enough time for crystals to grow large and the pressure is relatively small and doesn't cause a foliation to develop.

10. Hydrothermal Metamorphism: Hot fluids often circulate around cooling plutons and cause **metasomatism** to occur. Metasomatism caused by reactions between hot fluids and rock is also called hydrothermal metamorphism.
It is the origin of many economic ore deposits, such as the Bingham copper mine.

- **a.** They form when hot, often acidic fluids carry economically important elements and dissolved minerals, undergo chemical reactions in rocks and leave the valuable metals as ore minerals or as native elements.
- **b.** They typically are associated with plutons, which supply the heat that warms and mobilizes fluid.
- **c.** The rind of contact metamorphism around plutons is called an **aureole**
- **d. Gold deposits**. **Lode deposits** are vein-like accumulations of valuable material, usually a metal like gold or silver. Lode – type gold deposits occur where hydrothermal fluids that carried dissolved gold underwent a chemical reaction and precipitated the gold in the vein. The 'Mother Lode' is/was a huge gold lode deposit in California that was mined after the gold rush. Placer deposits consist of gold (or other metals) in river sediments (usually gravels). They form when gold – from a lode deposit – is eroded and washed down a river, then the gold collects in sediment left by the gold. When people 'pan for gold,' they are trying to get gold from placer deposits.

11. Dynamic Metamorphism: Rocks caught in active shallow- to middle-level crustal faulting undergo dynamic metamorphism. The terms "cataclasis" and "mylonitization" refer to this type of metamorphism.

- **a.** During fault ruptures, rock within the fault zone gets heated up and sheared - think of putting something in a mill or grinder under high temperature.
- **b.** Faulted rock may behave either brittle-like or ductile-like, or both, depending on the depth of crust and rock temperature.
- **c.** Highly foliated rocks develop like schists.
- **d.** The terms *mylonite* and *cataclasite* are used to name these types of metamorphic rocks

GEOLOGIC DATING

1. Know the basic principles and concepts behind the general approaches to dating earth materials and events - ***relative*** **dating** and ***absolute*** **dating**.

2. **Relative dating principles -** know these!

- **a.** Original Horizontality
- **b.** Superposition -
- **c.** Lateral Continuity
- **d.** Cross-cutting
- **e.** Fossil Succession
- **f.** Unconformity

3. Superposition, Fossil Succession, and Unconformity principles most useful on sedimentary rock packages.

4. Cross-cutting principle very useful for intrusions and faults.

5. Absolute dating techniques

- **a. Radiometric dating** - Use of radionuclides and their stable daughter products to get an absolute date for the formation age of a rock.
- **b.** Understand the **half-life** principle and decay constants.
- **c.** Be able to do a calculation based on a given set of parent-daughter ratios, and its half life.
- **d.** Igneous are most suited for this technique. Know why.

6. Development of the Geotimescale

- **a.** Know its origins
  - i. Relative dating principles (especially use of fossils) establishes relative time scheme early on
  - ii. Later establish real ages using absolute dating
- **b.** Know its major time divisions - eons, eras, periods, epochs.
- **c.** Know the names for the eras and periods