Structural Geology Introduction/Review of Basic Principles

I. Introduction

A. Definitions

1. Geology- study of lithospheric portion of the earth and its interaction with the biosphere, hydrosphere and atmosphere

2. Structural Geology- study of the architecture of rocks as related to deformation.

a. Structure = Latin Struere - to build

b. Study of the architecture of the Earth's crust

(1) Architecture = form, symmetry, geometry and the elegance of the components of the Earth's crust on all scales.

c. Rock Mechanics (Science) = strength and mechanical properties of crustal materials, both now and at the time they were formed and deformed.

3. Tectonics (Greek Tektos - builder)

a. Study of the forces and motion that result in rock deformation and structure

b. Tectonic Deformation of Rock

(1) Rigid Body Translation- transportation without any permanent change in size and shape

(2) Deformation - permanent change in the size and shape of rock by breaking or flow.

(a) Brittle Deformation- brittle fracture and cracking of rocks

i) low temperature, low pressure

(b) Ductile Deformation- flowage and solid-state change of shape

i) high temps, high pressure, but below melting point of rock.

B. Goal of Structural Geologist

1. To interpret and define, on the basis of scientific data, crustal dynamics.

a. Complex interaction of natural elements

b. Large-scale in both time and space
c. Large time scale = "non-repeatable" experiments

2. Geologic Reconstruction

a. Time is the limiting factor
(1) slow rates of process, very large scale

b. Solving jig-saw puzzle

(1) no picture on cover of box
(2) some pieces may be missing?
(3) Geologists reconstruct the picture with limited data and the complicating factor of time

C. Scientific Method

1. Observations of Nature
2. Hypothesis Construction: I.D. Relationships in Nature
3. Experimentation, Hypothesis Testing, More Observation
4. Accept or Reject Hypothesis
5. Creation of Model to Explain Observations
6. Further Model Testing
7. Accept or Reject Model as Proven Theory

- Science works by formulating observation-based models that can be tested by postdiction and prediction, then refined and tested again. The game is endless.

D. Goals of This Course

1. To learn the terms and concepts of structural geology
2. To fine-tune your skills of observation and conclusion
3. To orient rock structures in 4-dimensions of space and time
4. To learn about processes of rock deformation
5. To develop your cognitive skills (i.e. thinking!!)

II. Approaches to Structural Geology

A. Models of Analysis

1. Geometric Model of deformation

a. 3d interp. of form and orientation of struct
b. based on data obtained from field studies (mapping, geophysical data)
c. represented by cross sections and maps.

2. Kinematic Model

a. Reconstructing specific history of motion
b. Model of plate tectonics is a kinematic model

3. Mechanical Model

    a. Reconstructing the mechanical processes that resulted in rock deformation

4. Analytical Method

    a. Observations
    b. hypothesis
    c. model derivation
        (1) predictive capabilities
    d. additional data collection
        (1) model adjusment ** there is never "enough" data

B. Geometric Models

1. Questions

    a. What is the structure, its size, shape, orientation and relationship in time and space?
    b. What is its external form and internal fabric?

2. Basic tools

    a. Maps, cross sections, air photos, stereographs, surveying
    b. Field Mapping

3. Structural Analysis

    a. Observation and Description
        (1) 3-D geometry of rock structure
        (2) I.D. Geometric Relationships
    b. Reconstruct stresses (forces) that created the deformation pattern

4. Scale of Observations

    a. Microscopic- smaller than naked eye
    b. Mesoscopic- hand or outcrop level
    c. Megascopic- mountain-range level

        (1) Fractals and Structure

            (a) repetition of geometric patterns in a system at varying levels of scale
            (b) "Penetrative" Deformation: deformation found at all scales in rock body

C. Kinematic Models

1. Goal

    a. To interpret the changes of state that altered the location, orientation, size and shape of a body of rock.

2. Products of Analysis

   a. Restored Sections,
   b. partical paths,
   c. plate motion vectors,
   d. sense-of-shear,
   e. rotation,
   f. velocity

3. Strain Analysis

   a. Evaluating the changes in a body that result from dilation and distortion

      (1) dilation = volume change
      (2) Deformation > order in a structural system.

D. Mechanical Models

1. Goal

   a. To reconstruct forces, stresses, and mechanical aspects of the system.

   b. To I.D. "The power and workings of the engine driving the deformation."

2. Analysis by Delineation of:

   a. Rock strength,
   b. Deformation rate, and
   c. Boundary conditions of structural system.

E. Applying the Scientific Method to Geologic Problems: The approach of a good scientist

1. admits own ignorange, hence need for research
2. Finds own field difficult and full of holes
3. Advances by posing and investigating new problems
4. Welcomes new hypothese and methods
5. Proposes and tests new hypotheses
6. Searches for counter examples
7. relies on logic
8. uses mathematics
9. Cherishes the unity of science
10. relies on primary source, gathers and reduces data
11. Looks for counter examples
12. Attempts to find and apply universal laws
13. Settles disputes by experiment and computation
14. Is current
15. Seeks critical comments from others

EARTH MATERIALS: MATTER, MINERALS AND ROCKS

I. Basic definition of rocks and minerals

A. Rock - an aggregate of one or more minerals, i.e. mineral crystals are bound together or lithfied into an aggregate or rock.

B. Mineral - a naturally occurring inorganic solid, which possess a definite internal atomic structure, and a specific chemical composition.

II. Composition of Matter

A. Definitions

1. Elements - all matter are made of elements, over 100 elements are known. Elements include O, Au, Ag, N, H, C and have a unique, and identifiable atomic structure.

2. Compounds - combination of two or more elements joined together at the atomic level.

3. Atom - the smallest recognized particle of matter that retains the properties of a given element. Atoms of elements are combined together to form compounds.

V. ROCKS AND THE ROCK CYCLE

1. Three Rock Types (based on their mode of origin)

a. Igneous Rocks- a rock (or agglomeration of one or more minerals) that results from the cooling of magma, or molten rock. As the magma cools, minerals crystallize from the molten rock. Magma - molten or liquid rock beneath the earth's surface. Lava - magma extruded onto the earth's surface via a volcanic vent.

2. Basic Terminology

A. Magma - molten or hot liquid rock, originates beneath the earth's surface (up to 120 miles beneath), composed of elements found in silicate minerals, water vapor, and gases.

B. Lava - magma that is extruded onto the earth's surface via volcanic eruptions (hot magma is confined at depth beneath surface, relatively lighter than confining rock, rises upward, may eventually erupt onto earth surface).

C. Extrusive Igneous Rocks or Volcanic Ig. Rocks - rocks which solidify from lava (or were extruded onto earth's surface)

D. Intrusive Igneous Rocks or Plutonic Ig. Rocks - rocks which solidify from magma beneath the earth's surface.

III. Magma Crystallization Process

A. Hot, molten magma: ions of elements are moving freely in a fluid, unordered state, as magma cools, the ions slow and begin to form atomic bonds, arranging themselves in orderly patterns --- known as process of crystallization.

C. Rates of cooling strongly influence size of mineral crystals that develop from magma/lava.

1. Slow Cooling - few centers of crystal growth develop, ions allowed to migrate over larger distances - results in rather large mineral crystals .

2. Fast Cooling - many centers of crystal growth, ions readily bond together, results in smaller mineral crystals.

3. Very rapid cooling - if magma is quenched instantly, not sufficient time for ions to bond, results in randomly distributed ions frozen - referred to as glass similar to manmade glass.

VI. Naming Igneous Rocks - Based on compostion and texture of igneous rock. SEE CLASSIFICATION CHART ON P. 43.

A. Mafic Rocks (from Mag and Fe) - generally darker colored rocks relatively high in iron, magnesium, calcium and low in silicon. Associated with high temp. end of bowens Reaction Series.

E.g. Gabbro = plutonic = phaneritic = mafic composition
Basalt = volcanic = aphanitic = mafic composition (Ca-rich plag., and Pyroxene).

B. Felsic (from feldspar and silica) Rocks - generallylighter in color, high in silica, Na, Potassium - consist mainly of quartz, K-feldspar, and Plagioclase

e.g. Granite = plutonic = phaneritic = felsic composition
Rhyolite = volcanic = aphanitic = felsic composition

C. Intermediate - admixtures of both felsic and mafic, dominated by amphibole, intermediate plagioclase feldspar, biotite.

e.g Diorite = plutonic = phaneritic = intermediate composition
Rhyolite = volcanic = aphanitc = intermediated comp.

D. Ultramafic = very rich in iron and mag., olivine and pyroxene, Ca-rich plagioclase

e.g. intrusive variety only = Peridotite - common in upper mantle

SEDIMENTARY ROCKS

b. Sedimentary Rocks- rocks that are derived and formed at the earth's surface.

As igneous rocks are exposed at the surface, they undergo a process of weathering in which the atmospheric processes at the earth's surface slowly disintegrate and decompose the igneous rocks. Sediment is generated (e.g. sand or gravel) via weathering and subsequently transported by running water, gravity, waves, glaciers, wind and sediment is deposited. After sediment is lithified or cemented into solid rock (analogous to concrete).

Basic Terminology

B. Weathering - disintegration and decomposition of rock at or near the surface of the earth, fragmenting rock into particles

C. Sediment - fragments of rocks and/or minerals that are produced from the weathering of pre-existing rock

D. Erosion - incorporation and transportation of sediment by a mobile agent, usually water, wind, or ice.

VI. SEDIMENTARY ROCKS

A. Introductory statements/definitions:

1. Sedimentary derives from latin root meaning "settling" as in products of chemical and physical weathering settling or being deposited from a fluid.

2. Visualization - physical and chemical weathering attacks rock, breaks and dissolves it into small particles, sediment, then subject to transportative forces (gravity, water, wind, ice), generally moved downslope under force of gravity, to a resting place (ocean or sedimentary basin), where deposited, buried, compacted, lithified, converted into sedimentary rock.

2a. Lithification - refers to the process of converting loose sediment or mud into solid rock.

1) compaction - as sediments accumulate and become buried with time, the weight of overburden compress the deeper sediments and squeeze out fluids and compact the sediment, compressing clays together, clays act as binding agents.

2) cementation - solutions carry ions into pours between sediments, with time ions may be precipitated as cements under appropriate chemical condition. Common cements include calcite, silica, and iron oxide.

3. Sed. rocks account for only 5% of the earth's crust/lithosphere, however they cover 75% of the earth's surface exposures. The sedimentary environment is a surface environment (at surface pressures and temperatures)

4. As geologists we can examine modern day sedimentary processes, look at depositional forms and life in sediments, and then go to ancient lithified sequences of sed. rock and interpret their environment of deposition (e.g. river, shallow ocean, deep ocean, lagoon, lake, swamp). Sed. rocks are also where fossils are found providing evidence of past life on earth. (do not find fossils in igneous environment, may find remnants in met. env. in which sed. rocks have been deformed).

5. Sedimentary rocks are where we find many natural resources such as coal and oil, also many ore minerals are found in sedimentary rock "hosts".

B. Sedimentary Rock Types/Classification

Detrital vs. Chemical Sedimentary Rocks.

1. Detrital Sedimentary Rocks: "Detrital" = Fragmented Origin.

a. Composition: sediments composed of quartz, clay, feldspars, and associated array of just about any other mineral in lesser proportions (e.g. amphibole, or any of silicate/igneous minerals, as well as recycled sedimentary rocks).

E.g. Granite is weathered - produces quartz, and feldspars, plus mica: quartz is most resistant mineral and as a result is most common remnant product, feldspars and mica are generally chemically altered to clay minerals.

I.E. the composition of the original rock (ig., sed., met.) that is weathered will have a direct influence on the composition of the sediment/sed. rock that results.

b. Texture of Sediment: i.e. grain size. Particle size is the primary basis for classifying detrital sed. rocks. See table of sediment diameters and associated sedimentary rock classification (p. 87, TABLE 4.3) (note: clay has double meaning, is a mineral family, as well as a grain size). Grain sizes and corresponding rocks: silt/clay = shale or mudstone; sand = sandstone; granule to boulder = gravel = conglomerate or breccia.

Generally size of particles are reflection of the energy of the transporting medium: e.g. boulders must be related to massive river system with high energy, mud will only be deposited under conditions of very quiet or slack water.

c. Detrital Rock Types (shale, sandstone, conglomerate)

1. Shale - detrital sed. rock consisting of lithified clay and silt sized particles, very small particles < 1/16 mm (must use microscope to see particles), shale is used for such rocks which readily split into thin layers, if they do not then we refer to them as "mudstone". Generally associated with quiet water environments of deposition.

2. Sandstone - detrital sed. rock made up of sand sized grains. Sorting - degree to which sand is the same size, sorting says something of the agent of transportation. Generally wind provides for a more well sorted sediment than river water, mud flows/slides provide little sorting. (longer the transport action the more well sorted) Well rounded grains suggest long distance of transport, angular grains suggest short distance of transport. Also composition - longer subject to weathering and transport the more less stable minerals decompose into clay. Thus quartz rich ss may be more mature, where as a feldspar rich ss may not have undergone as much processing.

3. Conglomerate - lithified gravels (boulders, to pea sized sediment), often poorly sorted with finer sediment between gravel. conglomerate - well rounded gravel; breccia - very angular gravel. Again rounding and sorting tell something of depositional conditions.

d. Chemical Sedimentary Rock Types - result from process of chemical weathering, transport of atomic ions in water solution, and redeposition of ions as rock forming minerals in shallow lakes and seas. Chemical sediments may be directly precipitated under high concentrations of ions in water (e.g. halite/rock salt), or ions may be "fixed" by organisms living in the water in shells, accumulation of shells may then provide material for chemical sedimentary rock.

1. Limestone - composed of a mosaic of the mineral calcite ($CaCO_3$) and forms by either chemical precipitation or biochemical processes. Biochemical

processes account for 90% of the limestones. Fossilized shell fragments of sea critters accumulate on sea bottom, become buried one layer on top of another, become compacted, shell redissolve and recrystallize under pressure of burial, to form limestone. Coquina - shell fragments in tact, Chalk - made up of foram shells (microscopic organisms), Travertine, $CaCO_3$ deposited in caves in form of stalactites and stalagmites.

2. Dolomite - similar to limestone, but has Mg incorporated into $CaCO_3$, $CaMgCO_3$.

3. Chert - SiO_2, microscrystalline silica deposited from solution in open ocean. Commonly associated wtih skeletal fragments of microorganisms that SiO_2 as opposed to $CaCO_3$ (diatoms/radiolaria).

4. Evaporites - chemical sed. rock that result from precipitation of minerals via evaporation of water. E.g. halite/rock salt (NaCl) and Gypsum ($CaSO_4$). Commonly associated with shallow seas and brine lakes (e.g. Salt Lake). Ions derived from chemical weathering of rocks and transported via groundwater to lake basin.

2. Sedimentary Rock Classification System

a. see page 93, TABLE 4.4

Detrital Rocks - distinguished mainly by grainsize, composition to a lesser extent

Chemical Rocks - distinguished mainly by composition of minerals and fossils.

Clastic vs. nonclastic -

clastic = fragmental. E.g. sandstone is a clastic detrital rock, fossiliferous limestone is a clastic chemical rock,

non-clastic = massive, crystalline appearance; if limestone has no fossils evident, then would be considered non-clastic.

METAMORPHIC ROCKS

c. Metamorphic Rocks: Pre-existing sedimentary and/or igneous rocks may be subject to reheating or great pressures during mountain building and will react and recombine to form metamorphic rocks

A. Basic Terminology/Definitions:

1. Process of metamorphism involves transformation of pre-existing rock (ig. sed. or even met.) under temperature and/or pressure. Result in change in both composition/mineralogy; and texture of rock as well.

2. The "grade" or degree of metamorphism ranges from slight (low grade) e.g. >compaction; to very intense (high grade) where original mineral components can no longer be recognized.

3. Under conditions of heat and pressure, rocks will begin to deform "plastically", bend, minerals may partially melt and recrystallize into different forms. Rocks can deform and become folded in process of metamorphism.

Metamorphic may be in turn heated to the point of re-melting to form magma and igneous rocks.

III. Textural and Mineralogical Changes- under temps. and press. of metamorphism, pre-existing rocks may under go changes in mineralogy during the recrystallization process or may also have textures realigned

A. Foliation - color banding or mineral alignment in a metamorphic that results from pressure during metamorphism. e.g. gneiss.

B. Rock cleavage - slaty cleavage, common in slate or metamorphosed shale, tendancy for rock to split into thin sheets.

C. Schistosity - alignment of mica flakes into somewhat wavy planes in a metamorphic rock.

D. Foliation in rocks can only be discerned if there are compositional variations in the rock

E. Non-foliated texture- no banding is visible, common in rocks composed of one mineral of similar color and crystal size (e.g. limestone to marble)

F. Summary: Results of metamorphic process include: increased density/compaction of rock, growth of larger crystals during recrystallization, reorientation of minerals in layered or banded appearances, and a change of mineralogy (low temp to high temp., eg. clay----dewatered-----mica).

IV. COMMON METAMORPHIC ROCK TYPES (SEE TABLE 5.1, P. 110)

A. Foliated Metamorphic Rocks

1. Slate- finely crystalline foliated rock composed of microscopic mica flakes, excellent rock cleavage into thin flat slabs. Slate results from low grade metamorphism of shale.

2. Phyllite- foliated metamorphic rock, similar in appearance to slate, slightly higher grade of metamorphism, mineral crystals are slightly coarser but still generally fine, characteristically has a glossy/satiny appearance in comparison to slate.

3. Schists - foliated metamorphic rock with >50% platy minerals, commonly muscovite and biotite. Generally schists result from moderate to high grade metamorphism of shale, thus producing mica upon alteration of clays, bands of other silicates (quartz and feldspar) may also be present. Schist named according to its mineral content, schist dominated by mica with lesser amounts of quartz and feldspar, and also containing garnet as a metamorphic by-product, would be termed a garnet mica schist., chlorite schist, talc schist.

4. Gneiss - foliated metamorphic rocks with color banding, granular in appearance, common gneisses exhibit a granitic mineral composition containing quartz, potassium feldspar, and sodium feldspar. White bands = quartz and feldspar, dark bands = ferromagnesian minerals. Generally derived from granite, but may result from high-grade metamorphism of shale or any quartzo feldspathic rock.

Generally: slate---phyllite---schist----gneiss
finely xln---------------coarsely xln
low grade -----------------high grade
e.g. shale as parent rock

B. Non-foliated Metamorphic Rocks

1. Marble - coarse, crystalline rock whose parent rock was limestone or dolomite, when pure is white and composed of calcite, relatively soft used for carving

2. Quartzite - non-foliated metamorphic rock resulting from met. of sandstone, quartz grains fuse under moderate to high grade metamorphism

ROCK CYCLE Full cycle: magma-----cooling/crystallization---igneous rocks---weathering----sediment----lithification/compaction----sedimentary rocks---pressure and temperature----metamorphism----metamorphic rocks----remelting-----igneous rocks

BASICS OF TECTONICS

I. Introduction

A. The theory of plate tectonics is a recent development in the geological sciences, really accepted by scientific community since the early 1960's. Earlier in the century geologic paradigm was dominated by the belief that ocean basins and continental land masses were permanent and fixed on the surface of the earth. The theory of Plate Tectonics now recognizes that the positions of land masses are not fixed and that they have moved about the earth's surface over geologic history, ocean basins/oceanic crust are continually being created and destroyed through tectonic processes.

B. "Tectonics" - is a term that refers to the deformation of the earth's crust.

"Plate" - refers to the subdivision of the earth's crust and lithosphere into a number of tectonically coherent blocks that move about the earth's surface over long periods of geologic time, carrying with them continents and oceanic crust.

"Plate Tectonics" - refers to the formation and migration of these lithospheric plates, physical interaction between the plates, and the resultant deformation that is incurred by the crustal rocks during this process.

C. The Problem with proving and accepting the theory of plate tectonics lies in that it is a process which involves the whole of the earth and involves time spans on order of 10' of to 100's of million's of years, obviously practically impossible to observe directly. So the theory has beed deduced from evidence recorded in earth's rocks, often difficult to interpret and sometimes inconclusive.

II. Historical Perspective on the Evolution of Plate Tectonic Theory: Continental Drift a Precursor to Tectonic Theory

A. Continental Drift - Alfred Wegner (German earth Scientist)
proposed a hypothesis in early 1900's that the world continents have been drifting about on the earth's surface over hundred's of millions of years of geologic time.

1. Wegner suggested that a supercontinent of "Pangaea" existed 200 M.Y. ago in which all of major worlds continents were once amalgamated together, and have since broken apart and migrated or drifted to their present positions/configurations.

2. Wegner based this hypothesis on the apparent "jigsaw" like fit of South America and Africa if they were moved back across the Atlantic ocean. He also noted similarities of paleoclimate, fossil records, lithology, and rock structures between opposing coasts of each continent.

B. Evidence for Wegner's hypothesis of Continental Drift

1. Fit of the Continents: Wegner noticed that the coastlines of SAM and AF have complimentary shapes and that they may have onced fit together, but have since moved apart. Wegner was widely criticized for his ideas, as scientists had no conceivable process which might account for this drifting of continents, in the time frame of human observation, continents are apparently stationary.

a. 1960's Sir Edward Bullard and associates produced a computer generated map reconstructing the continental jigsaw puzzle via rotating continents and accounting for erosional irregularities of the coastlines. The reconstruction was very impressive!

2. Fossil Evidence

Wegner performed a literature search and noted that similar species of fossils or ancient life could be recognized between the east coast of SAM and the west coast of AF. Examples include the fern Glossopteris that was found in rocks of Africa, Australia, India, and SAM. It was known that these plants only existed in a subpolar climate, suggesting that not only was the climate different, but also an explanation for their wide distribution was also needed.

Similar evidence was also provided by fossil reptile of Mesosaurus which is only found on east coast of SAM and west coast of AF.

How did these critters migrate across the ocean basins? An explanation was needed, land bridges were originally proposed, but this was tenuous at best, continental drift could also explain the occurrences.

3. Similar Rock Types and Structural Rock Deformation

Similar rock types and structural features such as mountain belts were also note on continents of opposite sides of ocean basins. If continents are reconstructed, the Appalachian mountain belt forms a continuous chain with mountains on Greenland and in northern Europe. Thus similarity between coal fields of northern Europe and Appalachia.

4. Paleoclimatic Evidence

Wegner also detected similarities in paleoclimatologic data (ancient climate indicators) such as plant species and depositional environments for sedimentary rocks. Evidence for glacial conditions 250 m.y. ago are found in similar aged rocks from southern Africa, SAM, India and Australia (evidence such as glacial deposits and grooved rock surfaces), much of this land presently lies within 30 degrees of the equator, an area not known for its glaciers. So a theory was needed to explain these phenomenon.

Similar evidence also from fact that fossils in coal fields of Appalachians are indigenous to a warm subtropical climate, but are presently located in a 4 season temperate climate, a theory needed to explain the disparity.

** Wegner's ideas were generally considered as heresy within the scientific community and were not generally accepted except by closet "drifters". Major opposition to the hypothesis came as a result of a lack of explanation for a plausible mechanism in which continents could move about the earth's surface. How were the continents plowing through the crust, gravitational forces? or what?

III. Modern Plate Tectonic Theory

A. Basic Model - Based on early work by Wegner, more recent mapping of seafloor, magnetic surveys of earth's magnetic field, and observation of earth's seismic activity or earthquake activity.

1. Plates- Plate tectonics model suggests that the outer, rigid lithosphere of the earth consists of about twenty rigid segments known as "plates". See Fig. 13.6. These lithospheric plates ride on a semi-plastic material called the aesthenosphere in the upper mantle. Plates are thinnest over the ocean, and thickest over continents.

2. Plate Mobility - it is recognized that each moves as a distinct rigid unit in relation to other plates. These plates move on top of a semi-plastic aesthenosphere, and interact with one another along their boundaries. We find most of tectonic deformation of plates along their boundaries where plates crush and grind past one another leading to such occurrences as earthquakes, volcanism, and mountain building.

B. Plate Boundaries and Nature of Interaction between Plates

3 types of plate boundary interaction: Divergent, Convergent, or Transform fault boundaries

1. Divergent Boundaries - boundary condition in which tectonic plates move apart, resulting in upwelling of magma and volcanic material to create new seafloor: i.e. creation of new crust.

a. located at crests of mid-oceanic ridges, where plates move apart and molten rock is injected and cooled to form new seafloor.

b. Seafloor spreading- process of plate divergence and injection of magma.

E.g.Atlantic ocean basin, has undergone seafloor spreading over last 165 m.y. at avg. rate of 6 cm/year. Process of opening and closing of Atlantic ocean basin has occurred several in earth's history.

c. Seafloor spreading/rifting process: fragmentatin of continent is thought to be initiated by an upward movement of hot rock from below the continent. The cont. crust is bulged upward and extends and cracks. Large valleys form as downfaulting occurs to form rifts or rift valleys (e.g. East African Rift Valley). Rift valley widens with time and eventually may extend to ocean with subsequent infilling with ocean water (e.g. Red Sea). Rift continues to spread with magma injected, expanding the basin to become a full-fledged ocean basin

1) e.g. Red Sea in Middle East is an example of a very young ocean basin that is just beginning the process of seafloor spreading. Red Sea is termed a rift in which Arabian Peninsula is moving away from Africa.

d. Anatomy of Spreading Center: e.g. Mid-Atlantic Ridge

1) spreading center actually takes form of mid-oceanic ridge rising up to 10000 ft above sea floor. The ridge results from volcanic buildup of lava injected into spreading center, and also result of rocks being relatively hot and buoyant. As this new ocean crust cools, it contracts, becomes denser, and sinks to lower elevation.

2. Convergent Boundaries- plate boundaries in which two plates move toward one another or collide. Collision of one plate into another results in downbending of one plate and descent of that plate beneath the other, the descending plate eventually reaches a depth into the upper mantle where it is completely melted and reassimilated into the lithosphere

(destruction of crustal material)

a. subduction zone- a zone of plate convergence in which where an oceanic plate descends into the upper mantle beneath the overriding plate.

1) where the plate descends at its lowest point, a "deep ocean trench" may result and may be up to 6-7 miles deep.

b. Oceanic-Continental Plate Convergence- ocean crust(basalt) is more dense than continental crust (granitic) and thus tends to sink more readily over semi-plastic aesthenosphere, thus oceanic crust downbends and subducted beneath continental crust, thin layer of mud/sediment on oceanic plate is scraped, folded and deformed at the interface of the overlying plate.

1) subduction-related volcanism and volcanic arcs as oceanic slab descends into upper mantle, it is heated up to point that it will begin to melt, buoyant less dense magma may develop and accumulate until it rises into overlying continental crust, part of it will cool intrusively and part may extend to the surface of earth to form vocanoes.

a) volcanic arc - an arcuate chain of volcanoes on continental crust that result from subduction of oceanic crust beneath continental crust.

e.g. Cascade mountains in U.S., Andes in SAM, Sierra Mtns in CA are eroded core of volcanic arc.

c. Oceanic-Oceanic Convergence- one oceanic slab is subducted beneath another oceanic slab, similar to above only volcanic activity occurs on overriding oceanic slab, resulting in island arcs as opposed to volcanic arc. Volcanoes build up until they form islands at sea (e.g. Japan islands, mariannas islands)

d. Continental-Continental Convergence-
case where 2 plates carrying continental crust collide, results in cont.-cont. collision (e.g. India to China resulting in Himalayas, or Europe and NAM ....Appalachians). Involves seafloor between continents being subducted until collision occurs, during collision sediment and rock strata are squeezed and deformed, and buckled into mountains. Results in complicated mess, with volcanics too.

3. Transform Fault Boundaries: condition where plates slide horizontally past one another along a fault (or fracture along which there is movement) Crust is neither consumed nor destroyed. Transform faults connect convergent and divergent boundaries into a worldwide network of interconnected plate boundaries. Most transform faults are located along divergent boundaries, but some do intersect continents (e.g. San Andreas Fault in Ca).

IV. Plate Tectonics: Modern Version of Wegner's Continental Drift Hypothesis

A. Development of Modern Theory- during the period of mid-1900's many advances were made in technology regarding the study of the earth, particularly during after WWII. Many techniques were developed in which to map the ocean floor (out of search for German submarines with magnetometers and sonar) and to monitor seismic or earthquake activity around the world.

B. Evidence which turned the tide in support of Wegner's early ideas and the modern concept of plate tectonics

1. Magnetism and Paleomagnetism (result of search for German submarines in WWII)

a. Basics of Magnetism

1) Earth has a magnetic field about it with a magnetic north pole and south pole similar to a bar magnet with lines of magnetic force flowing from North to south. Magnetic poles align with geographic n and s poles, a compass needle is a free magnet and will align itself with the earths north pole.

2) Paleomagnetism - iron-rich minerals such as magnetite (Fe_3O_4) act as tiny magnets, when these minerals cool from a magma there is a temperature at which they align with the magnetic field of the earth (curie point), and once totally coolen, they are frozen compass record of the earth's magnetic field. Paleomagnetism is hence fossil magnetism of the earth recorded in rock record. Thus if a rock moves after it has recorded the earths magnetism, it is then possible to reconstruct its original position.

b. Polar Wandering - a sequence of lava flows of similar age were studied in Europe and U.S. during 50 and early 60's. Their paleomagnetic signature was examined and the apparent magnetic north pole which these rocks suggested was plotted on a global map. It was found that the magnetic north poles were not located where they are today, so either the Poles have wandered from where they were, or the continents have drifted. When similar aged rocks from U.S. and Europe were examined through time, it was found that they exhibited separate polar wandering paths which converged together at at approximately 250 m.y., suggesting that the continents have migrated instead of the poles. Once the continents stop migrating then the poles matched up. If we reconstruct the continents across the Atlantic Ocean then they each have same pole orientation.

c. Magnetic Reversals

Following WWII, it was discovered that the orientation of the earth's magnetic poles have not remained constant, that they have reversed many times in the past, i.e. the magnetic north pole has switched to the south pole and vice versa.

1) Normal Polarity -So rocks have been found with paleomagnetism similar to todays polar arrangement termed "normal" polarity

2) Reversed Polarity- rocks which indicate magnetic north pole at current position of south magnetic pole

3) Magnetic reversals at oceanic spreading centers or ocean ridges- upon investigating paleomag across ocean spreading centers, it was discovered that patterns of normal and reversed polarity rocks of similar age are symmetrically arranged about a spreading center or oceanic ridge. suggests that new ocean crust is continually being formed at spreading centers and is symmetrically moved outward from center through plate movement.

2. Evidence from Seismic Records of Earthquakes

a. the distribution of earthquake focii or origination points of earthquakes was examined around the world and at convergent plate boundaries or subduction zones. See

Fig. 13.16 and Fig. 13.17. It was found that most quake activity is found at active plate margins such as subduction zones and to a lesser extent along mid-oceanic ridges or spreading centers. Compatible with tectonic theory as these areas are tectonically active and undergoing deformation

b. also along convergent boundaries, it was found that earthquake focii are distributed along a plane from shallow to deep and clearly outline the descending/subducting slab in a subduction zone. Earthquakes occur in response to friction associated with slab as it descends into the lithosphere.

3. Evidence from Ocean Drilling

a. drilling of ocean sediments and dating of the sediments has given further credence to the spreading center theory of plate tectonics. It was found that sediments near oceanic ridges were thinner and younger and that sediments farthest away from oceanic ridges are oldest and thickest, thus supporting the idea of new ocean crust being formed at spreading centers.

4. Hot spots and the Hawaiian Islands.

a. the Hawaiian Islands and their extension the Emporer seamount chain, are a set of volcanic islands that are arranged linearly in a southeast-northwest direction in the Pacific Ocean. The volcanic rocks on these islands have been dated and it was discovered that the age of the volcanic islands is oldest to the northwest and youngest to the southeast at the presently active island of Hawaii. The results suggest a conveyor belt theory in which the mobile Pacific Plate is moving to the west northwest in this area, and a stationary "hot spot" in the underlying mantle is responsible for the volcanic activity.

V. Driving Mechanism for Plate Tectonics: what force causes the plates to move about the earth's surface?

A. Accepted Theory: Heat Transfer/Convection within Mantle

1. Model: the lower or inner portion of the mantle, near the core, is hotter than the upper mantle, this unequal distribution of heat results in circulation of heated, semi-plastic mantle material...warm, less dense material of lower mantle rises very slowly in regions of spreading centers, spreads laterally, cools, and slowly sinks back into the mantle and reheating process repeats, these mantle convection currents result in shear force being applied to overriding crustal plate and drive plate tectonic motion.

Obviously no direct way to observe this hypothesis, so it goes. other models include active subduction pull, under force of gravity; also hotspots/mantle plumes have been suggested as modes of plate motion.

I. **GEOLOGIC STRUCTURE REVIEW**

A. Mountains: topographically elevated portions of the earth that rise thousands to 10's of thousands of feet above surrounding low lands.

1. Mountains may be single isolated masses (e.g. Kilimanjaro a volcanic peak in East Africa, or Mt. Rainier)

2. or Mountains may form continuous chains extending for thousands of miles (e.g. western Cordillera region of SAM and NAM, near continuous mountain chain running from Tierra Del Fuego to Alaska).

3. Mountains may be youthful (steep and of large relief) (e.g. Himalaya's) or mature (gently sloping and of relatively low relief) (e.g. Appalachian's).

B. Orogenesis: refers collectively to the processes that result in the elevation of land areas to form mountains.

C. Lecture examines the processes that result in mountain building, presented in the context of plate tectonic theory.

II. Crustal Uplift

A. Evidence that continental crust of earth has been uplifted in mountainous areas:

1. presence of fossilized shells of sea critters found on top of mountains, suggests that between the time that the critters lived and the time they were found: that the animals died, were buried by sediment/mud, lithified into sed. rock, and subsequently deformed and uplifted into mountains.

2. wave-cut terraces along recently uplifted portions of the coast of California. Ancient benches that were cut by wave erosion are now elevated hundreds of meter above sea level.

B. Isostasy- the concept of floating lithosphere in gravitational balance. I.e. density contrasts between less dense crust/lithosphere and more dense aesthenosphere results in the lithosphere "floating" on top of the aesthenosphere.

1. mountainous areas are thickened portions of continental crust that extend deep into the aesthenosphere (roots of mountains).

2. oceanic crust on the other hand is denser than continental crust and is thinner, thus owing to its relatively low isostatic position relative to the aesthenosphere.

3. thus according to idea of isostacy, loading of crust will result in subsidence (volcanic piling, deposition of sediment in a basin, thrust loading), and unloading of the crust will result in uplift or bobbing up of crust (glacial melt, erosional denudation of landscape).

4. Thus as Mountain Ranges undergo denudation, erosional unloading results in isostatic adjustment and continued uplift of the mountains, isostatic adjustments, and further erosion as mountainous crust is thinned and deepest portions of mountains are exposed through time.

III. ROCK DEFORMATION- process of rocks becoming physically deformed as they are subjected to stress

A. Plastic vs. elastic vs. brittle deformation of rocks: rocks may respond to stress in the form of folding like paper (plastic deformation) or fracturing into blocks (brittle deformation) or may deform elastically (i.e. given volume of rock will return to its original size and shape after stress is removed)

1. brittle deformation of rocks is rather easy to recognize, analogous to hitting concrete with sledge hammer. Conditions of stress result in fracturing or rupturing of rocks.

2. elastic: stress is applied slowly under constant pressure, rocks return to original size and shape after stress is removed.

3. plastic deformation: a set of conditions must be met before rocks will deform plastically

a. relative heat, constant pressure, and time

4. Generally: as stress is applied to rocks at low temp, and low press, rocks will first deform elastically (with ability to return to original size and shape once stress is removed), once the level of stress exceeds the elastic limit of a given type of rock (i.e. the point or strentgh of a rock, with stress beyond which rock will fail), it will then either deform plastically or brittly.

IV. FOLDING OF ROCKS OR ROCK STRATA (LAYERS OF ROCKS)

A. Under components of horizontal stress: flat-lying layers of sedimentary/volcanic rocks may become bent into a series of folds (analogous to pushing and folding sheet of paper).

1. folding process results in shortening and thickening the crust

B. Fold Types

1. Anticlines-upfolded forms, results in older rocks becoming enclosed within younger strata

2. synclines-downfolded forms, results in younger rocks becoming enclosed within older strata.

a. symmetrical folds - both limbs of the fold dipping at same angle away from fold axis

b. asymmetrical folds - both limbs of the fold not dipping at same angle away from fold axis

c. overturned folds - condition in which one limb of fold has been tilted beyond vertical

d. plunging folds- axis of fold is tilted

3. Domes- more or less circular equivalent of anticline, oldest rocks exposed in center of dome

4. Basin- more or less circular equivalent of syncline, youngest rocks exposed in center of dome

C. Outcrops Patterns Associated with Folded Rocks

1. As rocks are folded, and subsequently subjected to erosion, regular patterns become evident in relation to type of rock that outcrops and age of the rock that outcrops in an area of folded strata. In essence, erosion exposes the interiors of the folds

2. Non-plunging Folds- axis of fold is horizontal, results in parallel bands of dipping strata about the fold axis

a. anticlines- oldest strata exposed along fold axis

b. synclines- youngest strata exposed along fold axis

3. Plunging Folds-axis of fold is tilted, results in alternating V-shaped bands of dipping strata oriented about the fold axis.

a. anticlines- oldest strata exposed in the center of the V, V points in direction of plunge of fold axis

b. syncline- youngest strata exposed in the center of the V, V points in opposite direction of plunge of fold axis.

4. Doubly Plunging Folds- fold axis is plunging in two opposite directions, results in a flattened oval pattern, or a double V-shaped pattern <<<>>>>.

a. anticlines- oldest strata exposed in center of flattened oval

b. synclines-youngest strata exposed in center of flattened oval.

V. FAULTING AND RELATED STRUCTURES

A. Faults - fractures withing the earth's crust along which movement or offset of crustal blocks has occurred.

1. Dip-slip faults- movement is vertical down the plane of the fault, movement along the inclination or dip of fault plane hence "dip-slip".

a. Normal Faults-faults in which crustal block above the fault plane (hanging wall) move down relative to crustal block below the fault plane (foot wall)

b. Reverse Faults- faults in which crustal block above the fault plane (hanging wall) moves up relative to crustal block below the fault plane (foot wall).

1. Thrust Fault- reverse fault with very low angle, or very gently inclined (<30o) fault plane.

a. associated with strong, horizontally oriented, compressional stresses.

2. Strike-slip faults- movement along fault is horizontal along the fault (similar to notion of transform faults in plate tectonics), i.e. offset is parallel to the trend or strike of the fault

plane.

a. Strike - the trend or compass direction of the line formed between the intersection of a horizontal plane with any inclined plane.

3. Oblique-slip faults- faults which have both vertical and horizontal components of movement.

4. Stress Regimes and Style of Faulting

a. Reverse/Thrust Faults- often associated with compression or squeezing of crustal blocks, rupture results when stress>strength of rocks. E.g. in association with convergent tectonic zones.

b. Normal Faults- associated with "pulling apart" or tensional forces exerted on crustal blocks. E.g. in association with rift zones or spreading centers in plate tectonics.

1. Grabens- crustal block bounded by two inward-dipping normal faults, crustal block downdrops to form a graben.

2. Horst- relatively uplifted crustal block flanked by two adjacent grabens.

B. Joints-in contrast to faults- fractures along which no appreciable movement has taken place.

1. joints serve as a by-product, or structural features that accommodate stress during tensional and shear stresses associated with crustal movements.

2. joints often occur in very low-stress regimes, with broad, gentle warping of earth's crust.

3. joints often serve as sights of enhanced weathering processes, may result in streams and rivers following their trends.

VI. MOUNTAIN TYPES

A. Folded Mountains (aka "complex mountains")

1. Mountain relief a result of erosion and dissection of portions of the earth's crust that has been folded and thickened.

2. Fold belts are also commonly associated with faulting, metamorphism, and igneous intrusion; although folding is the most conspicuous deformation style.

3. E.g. Alps, Himalaya's, Appalachian Mountains

B. Fault-Block Mountains

1. Associated with erosion and dissection of portions of the earth's crust that has been displaced and tilted along high-angle normal faults (in associatin ith tensional stresses)

2. E.g. Basin and Range Province of Nevada, Utah, Eastern CA, SE Oregon, AZ.

3. Often associated with precursory volcanic activity.

C. Upwarped Mountains

1. produced in assoication with broad arching or upwarping of the crust or of vertical uplift along high angle reverse faults.

2. e.g. Black Hills of S.D. and Adirondack Mtns. of NY e.g. of broad arching or uplift

3. Rocky Mtns of CO, NM result of vertical uplift, leave front range in which mantle of sed. rocks are tilted upward along high angle faults.

a. results in hogbacks or flat-irons of front range

V. MOUNTAIN BUILDING: THE PROCESS OF MOUNTAIN CONSTRUCTION

A. Processes of Mountain Building have been studied in a variety of mountainous terrains around the world, some of which are relatively recent developments (Cordillera, Island arcs of S. Pacific, Himalayas), some of which are older remnants of orogenic events (e.g. Appalachian Mtns., Ural Mtns of USSR)

B. Charcter of Mountain Belts

1. often include parallel ridges of folded and faulted sedimentary and volcanic rocks

a. sedimentary rocks: sed. rx. often included in Mtn-bldg. events were deposited long before the Mtn event, and were subsequently caught up in the deformation process.

2. zones of metamorphosed rock bodies

3. igneous intrusions

C. Orogenesis at Subduction Zones

TIME AND GEOLOGY

I. Law of Uniformitarianism- the present is the key to the past. A basic premise of the study of geology first presented by Scottish Geologist James Hutton in the 1700's.

The law states that the geological processes operating at present, have been operating the same throughout geologic history. With many pieces of the geologic puzzle missing, we have to assume that the processes have been operating the same throughout geologic time.

Historical Geology is the study of earth history. For geologists to adequately understand the geologic environment of a particular site, a basic sequence of geologic events or history of an area must be put together.

RELATIVE VS. ABSOLUTE GEOLOGIC DATING

Relative Geologic Time: earth history placed in the context of relative sequences of geologic events.

Absolute Geologic Time: uses radioactive elements contained within rock sequences to chemically and quantitatively determine the absolute age of that rock within the framework of statistical and/or experimental error.

II. RELATIVE GEOLOGIC TIME

A. Law of Original Horizontality- in a layer-cake geologic sequence of rocks, such as sedimentary rocks, it is assumed that the rock layers were first deposited horizontally under the force of the earth's gravity.

B. Law of superposition- in an undisturbed sequence of sedimentary rocks, the lowermost rock layers are the oldest, and the uppermost rock layers the youngest.

C. Law of Cross-cutting Relationships- " a disrupted pattern is older than the cause of the disruption". E.g. when a fault cross-cuts a sequence of sedimentary rocks, the rocks were deposited first, then cross-cut by the fault, otherwise they would have been undisturbed by the faulting event.

1. Cross-cutting geologic phenomena include: faults, volcanic intrusions, and erosional unconformities.

Unconformity- a surface of erosion in which part or all of a rock record may be removed.

D. Principles of Rock Correlation:

1. Physical continuity of rock bedding.
2. Similarity of Rock types
3. Correlation/similarity of fossils: based on theory of evolution and distinct periods of life forms on earth.

a. Law of Faunal Succession: species of life have historically succeeded one another in a definite and recognizable order.

b. Index fossils: a relatively rare fossil, known only to have existed for a very short period of time, also of limited geographic distribution.

e.g. trilobites found only in Cambrian and lower Ordovician
e.g. sharks found throughout geo-history since Devonian

c. fossil assemblage: a series of fossils when found together, indicate a distinct time zone.

D. Relative Geologic Time Scale: broken into Eras, Periods, Epochs in decreasing time interval

Eras: Precambrian, Paleozoic, Mesozoic, Cenozoic

Periods: Paleozoic: Cambrian, Ordovician, Devonian, Mississippian,Pennsylvania, Permian

Mesozoic: Triassic, Jurassic, Cretaceous
Cenozoic: Tertiary, Quaternary

Epochs: Tertiary: Paleocene, Eocene, Oligocene, Miocene, Pliocene Quaternay: Pleistocene, Holocene

III. ABSOLUTE GEOLOGIC AGE DATING

A. Radiometric Dating- chemical/analytical method for determing the amount of radioactive decay that has occurred to a radioactive isotope (contained in a rock or mineral).

1. Radioactive Decay Series: process that occurs whereby unstable radioactive elements (e.g. Uranium) decay or breakdown into subatomic particles in order to attain a more stable atomic structure.

"Parent" = initial radioactive isotope (e.g. U-238)

"Daughter" = final end product that results from decay process (e.g. Pb 206)

For e.g. U-238 loses 32 protons during the decay process, resulting in an atomic no. of 206, defining the element lead. For a given radioactive element, it has been experimentally determined that the rate of radioactive decay is constant.

Rate of radioactive decay determined in terms of "half-life" = amount of time it takes 1/2 the amount of a given quantity of Parent isotope to decay into Daughter product.

e.g. T1/2 for U238 to Pb206 = 4.5 billion years; i.e. it takes 4.5 billion years for one/half of a given amount of U238 to decay into PB206.
Given the rate of decay for a given radioactive isotope: it is possible to measure the amount of parent isotope and amount of daughter isotope in a given rock specimen, and work back to the age of that rock.