I. Igneous rocks
   A. definition
      1. rocks formed from the cooling of molten rock, or magma
   B. constituents of magma
      1. primarily elements that form silicate minerals
      2. volatile gases and water
      3. minor amounts of rarer elements
   C. source of magma
      1. great depths (on the order of 200 km)
      2. has to be hot enough to melt rock
      3. rises because it is lighter than the surrounding rocks
   D. gross classifications
      1. extrusive
         a) magma that reaches the surface in molten form
         b) also called volcanic
      2. intrusive
         a) cools and solidifies before reaching the surface
         b) also called plutonic

II. Crystallization of magma
   A. cooling magma contracts
      1. atoms become more closely packed together
      2. individual atoms have less energy
   B. atoms begin to organize into molecules
      1. held together by ionic or covalent bonding
      2. silicate tetrahedron is one of the first molecules to form
   C. different minerals crystallize at different temperature/pressure
      1. initial crystals are suspended in the magma
      2. crystallization affects the composition of the magma
   D. lots of little crystals form throughout the cooling magma
   E. crystals will continue to grow until they interfere with each other
   F. eventually crystals interlock into a solid mass
   G. rate of cooling influences the crystallization process
      1. slow cooling leads to larger crystals
      2. fast cooling leads to lots of small crystals
      3. instantaneous cooling results in unordered atoms, or glass
      4. first crystals to form show more complete development
         a) plenty of room to grow

III. Important characteristics of Igneous Rocks
   A. texture
   B. mineralogy/chemistry

IV. Texture of igneous rocks
A. texture
   1. refers to the size of individual mineral crystals
   2. tells a lot about how the rock formed, particularly how it was cooled
B. phaneritic texture
   1. coarse grained texture
   2. individual crystals can be seen by eye
   3. implies slow cooling at depth
   4. exposure at the surface implies uplift and erosion
C. aphanitic texture
   1. very small mineral grains
   2. too small to be identified with the naked eye
   3. results from fast cooling at, or very near the earth’s surface
   4. often contain vesicles
      a) open spaces result from trapped gas bubbles
      b) common in lava flows
D. porphyritic texture
   1. deeply buried magma may take millions of years to cool
   2. relatively large crystals form during cooling
      a) high temperature minerals crystallize first
      b) sink slowly towards the bottom
   3. if the partially solid magma is cooled quickly
      a) large crystals (phenocrysts)
      b) frozen in an aphanitic groundmass
      c) called a porphyritic texture
E. glassy texture
   1. smooth surface that may appear to be polished
   2. no visible mineral grains (even with microscope)
   3. occurs when magma is instantaneously quenched
      a) ejected into a cool atmosphere
      b) insufficient time for atoms to organize into a coherent crystalline form
F. pegmatites
   1. very large mineral crystals
      a) may be feet or meters long
   2. tend to form in wet magma bodies
      a) water increases mobility of atoms within the melt
   3. can form veins when injected into country rock
   4. important sources of some minerals

V. felsic (granitic) rocks
A. basic characteristics
   1. rich in potassium feldspar and quartz
      a) among the last minerals to solidify (Bowen)
      b) high SiO2 content
2. magma is viscous (thick and gooey)
   a) high silica content
   b) will be important later

B. granite
   1. intrusive form of felsic rock
   2. phaneritic rock
   3. about 50% potassium or sodium feldspar
   4. 25-35% quartz
   5. dark silicates make up most of the rest
      a) biotite and amphibole
   6. often associated with the mountain building process
   7. forms the core of many mountain ranges

C. rhyolite
   1. extrusive form of felsic rock
   2. aphanitic equivalent of granite
   3. much less common than granite
   4. forms pretty volcanoes

D. obsidian
   1. glassy form of felsic rocks
   2. formed by ejection of pyroclastic material
   3. small amounts of dark minerals tend to dominate the color
   4. used by early humans for cutting tools
      a) fractures easily to form sharp edges
      b) high quartz content makes it hard

E. pumice
   1. light vesicular rock formed from felsic lava
      a) glassy texture
      b) usually found with obsidian
   2. formed by ejection of pyroclastic material
   3. gas bubbles are trapped during cooling
      a) granitic magma is viscous
      b) bubbles are unable to escape
      c) pumice forms from sort of a “froth”
   4. bubbles may make up 50% of the rock
      a) light weight
      b) will often float
      c) looks somewhat like a sponge

F. tuff
   1. made up of rock fragments ejected from a volcano
   2. typically ash-fall or ash-flow
   3. fragments may be welded together (welded tuff)
      a) implies fragments were very hot when they fell
   4. cooler fragments may form non-welded tuff
   5. lots of tuff in southern Nevada
a) Yucca Mountain is made up of tuff

VI. Mafic (basaltic) rocks
A. basic characteristics
   1. dark, dense igneous rocks
   2. rich in Fe and Mg
   3. basaltic magma has low viscosity (thin and watery)
      a) low silica content
      b) will be important later
B. basalt
   1. most common extrusive igneous rock
   2. dark green to black fine grained volcanic rock
   3. flows well and often forms shield volcanoes
   4. 3 km thick layers in WA, OR
   5. forms upper layers of the oceanic crust
C. gabbro
   1. intrusive equivalent of basalt
   2. both have lots of pyroxene and calcium rich feldspar
   3. probably a major component of the oceanic crust
   4. not common in the continental crust
D. scoria
   1. mafic equivalent of pumice
   2. dark hard rock
   3. contains lots of vesicles
   4. if there are few vesicles it is called vesicular basalt

VII. Intermediate (andesitic) rocks
A. basic characteristics
   1. composition intermediate between basaltic and granitic
   2. light colored, but generally low in quartz
B. andesite
   1. medium-gray, fine grained rock
   2. characteristic of the Andes mountains
C. diorite
   1. the intrusive form of andesite,
   2. distinguished from granite by the lack of quartz crystals

VIII. Ultramafic rocks
A. basic characteristics
   1. low silica content
   2. rich in iron and magnesium
   3. mostly olivine with pyroxenes and amphiboles
B. peridotite
   1. coarse-grained dark green-gray rock
   2. dominant rock type in the mantle
C. no common extrusive form

IX. How do rocks melt?
A. magma is believed to form in the upper mantle
   1. not the core as one might expect
B. what can turn rock into liquid?
   1. we can melt hot rocks by adding water, raising temperature, or lowering pressure
   2. adding water
      a) lowers the melting point
   3. raising temperature
      a) the earth gets hotter with depth (geothermal gradient)
      b) if rock moves downwards, it will get hotter
   4. reduced pressure – decompression melting
      a) lowering pressure lowers the melting point
      b) mechanism
         (1) bring the rock closer to the surface
         (2) reduce the amount of rock above it
C. partial melting
   1. not all of the affected rock will necessarily melt,
   2. produces rocks that are more granitic than the original
      a) granitic rocks solidify/melt at low temperature
   3. the ‘granitic’ minerals in a basalt will melt easier

X. Where does magma form?
A. mantle
   1. hot rock rises at divergent boundaries
   2. hot rock rises at points called mantle plumes
B. subduction zones
   1. oceanic plate is driven downwards
      a) carries water saturated sediment
      b) some sediments are scraped off at the edge
   2. temperature increases with depth
      a) some of the rock may melt
      b) water driven off may help melt some of the overlying plate
   3. partial melt
      a) accumulates to form magma body
      b) low-melting point rocks tend to be felsic
      c) leads to felsic magma

XI. Bowen’s Reaction Series
A. Bowen melted rocks and minerals, observed melting/cooling
B. conclusions
   1. different minerals crystallize at different temperatures
   2. composition of the liquid changes during solidification
      a) melt becomes depleted in some elements
      b) relatively enriched in others
   3. solidification follows one of two pathways
a) path depends on initial composition of the melt
   b) iron/magnesium versus calcium/sodium/potassium
   c) mineral formation during cooling follows the appropriate reaction series

4. solid crystals on both branches of the reaction series react with the melt
   a) forms the next mineral in the series
   b) this reaction rarely goes to completion

5. solid crystals on the central branch of the reaction series do not react with the melt

XII. Magmatic differentiation

A. process by which different rocks can form from a single magma
   1. we think the mantle is more uniform than surface igneous rocks
   2. composition of the mantle is thought to be ultramafic,
   3. so where does granite come from
   4. differentiation does not fully explain granite

B. differentiation occurs within a magma chamber
   1. large (km’s) cavity filled by magma
   2. grows upwards
      a) magma pushed rock aside
      b) magma melts the country rock

C. fractional crystallization
   1. dense crystals (e.g., olivine) commonly form early in cooling
   2. chances are they’re going to sink
   3. phenomena is called crystal settling
   4. changes composition of the remaining magma
      a) olivine removes Fe, Mg, Si, O
      b) lighter elements become more important
   5. a single magma can form several rock types in a vertical column

D. assimilation
   1. as magma moves upward it pushes aside existing rocks
   2. also assimilates some of the existing rock
   3. if magma is hot enough to melt the old rock
      a) it becomes assimilated
      b) changes melt chemistry
   4. if the melt is not hot enough
      a) old rock becomes embedded in the magma
      b) forms xenoliths
      c) of course, partial melting can also occur

E. magma mixing
   1. rising magma may overtake another magma body
   2. the two may have different compositions
a) possibly originate at different depths
b) more likely, different sizes
   (1) degree of alteration will vary with size
      (a) differentiation, assimilation
      (2) different rates of rise, cooling

3. magma bodies join through complicated mixing process

XIII. Igneous intrusions

A. intrusive structures
   1. result from subsurface emplacement (cooling) magma
   2. generally called plutons
   3. classified on the basis of size and physical characteristics
      a) tabular or massive
         (1) tabular takes on a ‘book’ shape
         (2) massive is a shapeless blob
      b) discordant or concordant
         (1) discordant cuts across existing rock layers
         (2) concordant goes with existing rock layers

B. batholiths
   1. large (huge) massive discordant bodies
      a) must have a surface exposure of >100 square km
      b) otherwise it is called a stock
   2. usually granitic in composition
   3. upper portions of batholiths may contain inclusions of the
country rock that was displaced; these are called xenoliths
   4. batholiths often form in groups
      a) groups may be 100’s of km long
      b) may extend 10’s of km deep
      c) commonly form the core of mountain ranges

C. dikes
   1. discordant tabular bodies
   2. form when magma is injected into fractures
   3. usually vertical
   4. usually a few meters thick and several km long
   5. often alter the adjacent rock
      a) intense heat from molten rock
      b) chemical reactions

D. sills
   1. concordant tabular bodies
   2. inserted between layers of rock
   3. can be a km thick
   4. often formed from easily flowing basaltic magma
   5. these resemble buried lava flows
      a) except there are no flow tops
      b) there is often alteration of the rock above
E. lacolith
   1. special case of a sill which forms from viscous magma
   2. tends to form a hump in the center
   3. may be several km across

XIV. Nature of volcanic activity
   A. basic mechanism
      1. magma is lighter than the rocks above
      2. density difference causes it to rise
      3. as it rises
         a) magma cools
         b) pressure lowers, causing gas to expand
         c) expansion reduces density, speeding the rise
      4. pressure of gas expansion may open a vent to the surface
      5. magma leaves through the vent
      6. mellow or explosive depending on magma composition
      7. eruption lowers pressure in magma chamber
         a) causes more outgassing
         b) lowers the magma density, speeds rise
   B. effects of viscosity
      1. low viscosity magma
         a) tends to flow easily
         b) allows gases to escape
         c) Hawaiian volcanoes
      2. high viscosity magma
         a) tends to plug up the vent
         b) prevents escape of gases
         c) pressure build up can cause explosive eruption
   C. controls on viscosity
      1. primarily controlled by silicon content
         a) the more there is, the thicker the magma will be
         b) granitic magma is thicker than basaltic
      2. temperature
         a) viscosity decreases with increasing temperature
         b) much less important than silicon content
      3. gas content
         a) viscosity decreases with increasing gas content
         b) much less important than silicon content
         c) gas also makes magma more explosive

XV. Lava flows
   A. basaltic lava is very fluid
   B. tends to flow easily in thin sheets
   C. as the lava advances it cools
      1. surface starts to solidify
      2. forms a distinctive texture
D. pahoehoe lava  
   1. fast moving (up to 30 km/hr) watery lava  
   2. surface forms smooth wrinkles as it solidifies  

E. aa lava  
   1. more viscous, slower flowing (5-50 m/hr)  
   2. forms a harder skin  
   3. breaks into sharp fragments as it solidifies  
   4. looks like moist tilled soil  
   5. difficult to walk on  

F. sheets of cooled lava often contain lava tunnels  
   1. allows lava to move far from the source  

G. pillow lava  
   1. lava flows entering water are quenched  
   2. forms pillow sized and shaped blocks  

XVI. Volcanic Gases  
A. most magmas contain ~1-6% gases by weight  
   1. mostly water vapor  
   2. also ammonia, sulphur compounds (acid rain)  
   3. gases are contained in solution like in soda  
B. probably formed earth’s atmosphere and surface water  
C. driving force for volcanic eruptions  
D. probably creates volcanic vents  
   1. gas pressure ruptures rock above magma chamber  
   2. provides a conduit to the surface  
E. gases also affect viscosity of lava  
   1. more gas means less viscous  
F. vesicles  
   1. bringing lava to the surface is a huge pressure drop  
   2. gas comes out of solution  
   3. forms bubble shaped cavities called vesicles  
   4. rock is called vesicular basalt (or tuff), scoria, pumice  

XVII. Pyroclastic materials  
A. term for material violently ejected during a volcanic eruption  
B. ash and dust  
   1. thin skin surrounding gas bubbles solidifies and shatters rapidly on contact with the atmosphere to produce shards  
   2. falling ash can form thick layers of volcanic rock called tuff  
      a) non-welded if the ash is “cool” when it lands  
      b) welded tuff if the ash is still partially molten  
   3. dust can stay suspended in the atmosphere for significant amounts of time and have climatic effects  
      a) blocks sun light  
      b) Krakatao (1800’s) cooled the earth for ~1 year  
C. cinders
1. pea sized particles
2. fall closer to the source than ash does

D. pumice
1. light rock characterized by lots of air bubbles
   a) probably from volcanic ‘froth’
2. often associated with obsidian

E. larger pyroclastic ejecta
1. baseball size and larger chunks
2. blocks if the outer surface is solid when ejected
3. bombs when the outside is molten

F. pyroclastic flows
1. major hazards associated with volcanic eruptions
2. lahars
   a) volcanic mudflows
   b) consist of water saturated volcanic ash
3. nuee ardente
   a) also called glowing avalanche
   b) incandescent gases and dust that flow from volcano
   c) flows downhill rapidly (~100 mph)
   d) one of the most lethal phenomena on earth
   e) 28,000 dead in Martinique, 1902

XVIII. Types of volcanoes
A. common features
1. volcanic vent - narrow tube that leads upward from a subterranean magma chamber to the earth’s surface
2. volcano - mound of volcanic debris surrounding a volcanic vent
3. central crater - collapse feature at the center of a volcano, if it is more than 1 km across it is called a caldera
4. lava tubes – horizontal tubes that will bypass a plugged vent

B. shield volcano
1. low viscosity (thin) lava flows out to form a shield
2. the Hawaiian islands are a prime example
   a) island of Hawaii is about 1 million years old,
   b) formed from 5 major volcanoes
   c) stands about 30,000 ft above the ocean floor
   d) largest mountain on earth
   e) not steep
   f) new island is forming offshore
3. as a shield volcano ages
   a) it’s lava becomes more viscous
   b) eruptions tend to become more sporadic
   c) produces more pyroclastics,
   d) flank eruptions become more frequent
e) the cone becomes steeper

C. cinder cone
   1. formed when chunks build up around a vent
   2. pyroclastic activity implies a viscous (silicon rich) magma
   3. largest ones on earth are about 1000 ft high
   4. usually less than 100 ft high
   5. often found on the flanks of larger volcanoes

D. composite cone
   1. the classic volcano (Mt. Fujiama, Mt. Ranier, Mt. St. Helens)
   2. also called stratovolcano
   3. very steep sides, can be very high (> 15,000 ft.)
   4. formed by alternating processes
      a) pyroclastic ejection
      b) flows of viscous andesitic lava
   5. these are the violent ones

E. fissure eruptions and flood basalts
   1. basalt can flow from cracks in the earth
      a) primarily occurs at mid-oceanic ridges
      b) has also occurred on land (OR, WA)
   2. small-scale activity in Iceland
   3. no major events in recorded history

XIX. Volcanic landforms

A. crater
   1. bowl shaped depression at the top of most volcanoes
   2. lava bubbles up and over and then collapses back
   3. less than 1 km across

B. caldera
   1. collapse of a magma chamber
   2. at least 1 km across
   3. can be large ~50 km across
   4. can become active again or resurgent
   5. eruption of a resurgent caldera is a big deal
   6. Yellowstone caldera ejected >1000 km^3 of material 600K years ago

C. volcanic dome
   1. bump found within a crater
   2. form at end of eruption
   3. felsic magma too viscous to be erupted
   4. collapses back into the vent to plug it
   5. often forms island in a crater lake

D. diatremes
   1. matter ejected from great depth that solidifies within the vent
   2. kimberlite pipes are diatremes that bear diamonds
3. Shiprock is a diatreme that was exposed by removal of the surrounding rock

XX. Distribution of volcanic activity

A. where are volcanic rocks produced?
   1. volcanoes that extrude andesitic to granitic magma
      a) continental boundaries
      b) islands adjacent to deep-sea trenches
   2. basaltic lava (volcanoes and flood basalts)
      a) ocean basins
      b) continental interiors
      c) most volcanic rock is produced by seafloor spreading

B. spreading center volcanism
   1. seafloor spreading creates a rift in the oceanic crust
   2. lowers pressure on the underlying mantle
   3. reducing pressure lowers the melting point of rocks in the mantle (primarily peridotite) which partially melt to form basaltic magma

C. subduction zone volcanism
   1. magma is generated within the descending plate at a subduction boundary
   2. as the rocks descend they heat up from the geothermal gradient
   3. low melting point minerals and volatiles mobilize and rise up through the overlying plate;
   4. leading to partial melting and formation of a magmatic body

D. intraplate volcanism
   1. continental interior basalt flows and island volcanoes away from plate boundaries are thought to originate from ‘hot spots’ created by plumes of rising mantle material
   2. more than 100 such hot spots have been identified

XXI. Volcanic hazards

A. flowing lava
   1. velocity depends on viscosity and slope
   2. usually fairly slow
   3. property damage is absolute
   4. some success at diversion by cooling

B. eruption debris (bombs, blocks)
   1. lethal within a limited radius
   2. not associated with all volcanoes
   3. resurgent caldera would be an immense blast

C. nuee ardente
   1. no hope
   2. limited travel distance
   3. they follow stream valleys
D. directed blast
   1. little hope of survival
   2. range of a couple miles
   3. Mt St Helens
E. ash fall
   1. burial in red hot rock, oh boy
   2. thick carpet over several miles
   3. possible climatic effects
F. lahar
   1. mudflow of volcanic ash
   2. during the eruption ash chokes and dams rivers, bad
   3. several years later can be worse
      a) overtopping of a crater lake
      b) snowmelt from a winter eruption
G. flank collapse
   1. massive landslide associated with an eruption
   2. Mt. St Helens had a flank collapse
   3. worst if it is an island volcano
   4. Mauna Loa could create a massive tsunami
H. resurgent caldera
   1. special
XXII. Volcanic benefits
A. ash produces great soil
   1. rich in minerals
   2. weathers quickly
   3. highly porous
B. hydrothermal emplacement of precious metals
   1. water, gases, and rare elements are concentrated
   2. released as hydrothermal fluids
   3. follow faults and fractures
   4. may deposit, gold, silver, lead, etc.
C. black smokers
   1. undersea vents
   2. sea water circulates and picks up metals
   3. precipitates on sea floor
   4. not currently being mined
D. geothermal energy
   1. intrusions stay warm for a long time
   2. water entering intrusions gets hot
   3. nice source of energy, NV, CA, Iceland, New Zealand
   4. water can be superheated to > 100˚C