I. **Weathering**
   A. surface of the earth is a dynamic environment
      1. mountain building uplifts portions of the crust
      2. other processes work to level the earth’s surface
         a) mass wasting
         b) erosion
         c) weathering
   B. mass wasting
      1. transfer of rock and/or soil down slope through the direct action of gravity
      2. essentially landslides
   C. erosion
      1. removal and/or transport of earth materials through the action of moving water, wind, or ice
      2. covered elsewhere
   D. weathering
      1. decomposition of rock at or near the earth’s surface
      2. results from mechanical or chemical action,
      3. occurs because rocks are not at equilibrium
         a) rocks are initially formed at depth
         b) surface conditions are different
            1) temperature
               a) much cooler at the surface
               b) temperature changes in cycles
            2) pressure is lower at the surface
            3) weather/atmosphere
   E. weathering, mass wasting, and erosion work together
      1. weathering weakens and fragments intact rock
      2. it can be moved by mass wasting or erosion
      3. movement exposes new rock to weathering

II. **Chemical weathering**
   A. fundamentals
      1. chemical decomposition of rock
      2. forms components more stable at the earth’s surface
      3. water plays a leading role in chemical weathering
         a) most reactions occur in solution
         b) lack of water severely retards chemical weathering
      4. principal processes
         a) dissolution
b) oxidation  c) hydrolysis

B. dissolution
1. occurs when the mineral is soluble in water
   a) simply dissolves into flowing water
   b) most minerals are insoluble in pure water
   c) small amounts of acid dramatically can increase solubility
2. normal acidification of rain water
   a) absorb CO$_2$ from the atmosphere
   b) forms weak carbonic acid
3. further acidification of groundwater
   a) additional CO$_2$ in soil gas adds to acidity
   b) decay of organic matter produces humic acids
4. other sources of acid
   a) oxidation of sulfide minerals, particularly pyrite
   b) forms sulfuric acid
5. calcite
   a) primary mineral in limestone
   b) highly susceptible to acidic water
   c) dissolution of calcite
      (1) puts the Ca ion in solution (hard water)
      (2) releases CO$_2$ gas
   d) caverns form when acidic water dissolves limestone
   e) used to neutralize acidic waters

C. hydrolysis
1. hydrogen (from water) replaces an element in the mineral structure to
   form a new, and more stable mineral
2. the atom that is freed becomes mobile
3. hydrolysis of feldspars
   a) forms clay minerals
   b) releases silica and metallic ions
4. quartz itself is pretty insoluble so is left behind
5. acidic water helps hydrolysis
6. acid rain on igneous rocks can be a serious problem (releases metals,
   e.g., Al, Cu, Zn)

D. oxidation
1. chemical reaction in which an element gives up electrons to, and joins
   with oxygen atoms
2. $4\text{Fe} + 3\text{O}_2 \rightarrow 2\text{Fe}_2\text{O}_3$ (hematite, rust)
3. important weathering mechanism
   a) strongly affects FeMg minerals and sulfides
   b) usually occurs in conjunction with hydrolysis
4. acid mine drainage
   a) mining exposes lots of fresh surfaces for weathering
b) oxidation of sulfide minerals also yields sulfuric acid

III. Mechanical weathering

A. fundamentals
   1. fragmenting of intact rock into smaller pieces
      a) process is purely mechanical
      b) pieces retain chemical properties of the original rock
   2. frees particles for transport
   3. increases surface area
      a) chemical action occurs on exposed surfaces
      b) fragmentation enhances chemical weathering

B. principal types of mechanical weathering
   1. frost wedging
   2. unloading expansion
   3. thermal expansion
   4. organic activity
   5. erosion
      a) performed by moving wind, water, or ice
      b) we’ll cover erosion separately

C. frost wedging
   1. water expands by about 9% when it freezes
   2. applies considerable pressure
   3. water seeps into small cracks in rocks
      a) macroscopic fractures
      b) microscopic fractures along crystal boundaries
   4. expansion during freezing enlarges the crack
   5. daily cycle in mountainous mid-latitude regions
   6. frost wedging often leads to formation of a talus slope

D. unloading
   1. rock strength
      a) rocks are very strong when compressed
      b) relatively weak under tension
   2. lithostatic pressure
      a) most rocks form deep in the earth
      b) weight of the material above applies force
         (1) confining pressure
   3. exhumation
      a) occurs when overlying material is removed
         (1) erosion
         (2) excavation
      b) confining pressure is removed
      c) rock tries to expand
      d) produces tensile stress
      e) most rocks, don’t respond well to tension
(1) crack during unloading
(2) particularly true for plutonic igneous rocks
f) same process occurs in mines and quarries
   (1) often occurs suddenly (rock burst)
4. unloading fractures
   a) usually parallel to ground surface
   b) plutonic rocks can form rounded structures
      (1) called exfoliation domes
      (2) somewhat like an onion skin
E. thermal expansion
   1. daily surface temperatures in deserts can change >30°C
   2. minerals may have different expansion rates
   3. cracking occurs from differential expansion
   4. field evidence implies that this happens, but laboratory tests have not successfully recreated the phenomenon
F. organic activity
   1. plant roots invade small cracks
   2. root growth enlarges the cracks
   3. burrowing animals remove loose matter
      a) open up pathways for other processes
G. general effects of rock fractures
   1. not all rock fractures result from unloading
   2. cooling and tectonic activity are also important
      a) occur prior to exposure of the rock mass
   3. in addition to fragmenting a rock mass, fractures provide pathways for water, and opportunities for other weathering mechanisms

IV. Rate of Weathering
A. controls on rate of weathering
   1. minerals present
   2. weather
   3. shape and surface area
B. mineralogy
   1. weather follows Bowen’s reaction series
      a) high temperature minerals (olivine) weather easiest
         (1) form at high temperatures and pressures
         (2) environment is very different from the surface
      b) low temperature (quartz) are more durable
         (1) form in an environment more similar to the earth’s surface
         (2) hence it is more stable there
C. climate
   1. tropics have the fastest weathering, arctic the slowest
   2. warm temperature speeds chemical activity
   3. most reactions won’t occur without water
4. organic growth produces humic acids
5. topography (slope) plays a role
   a) organic growth
   b) amount of water
   c) solar heating
D. shape/surface area
   1. bigger the surface area, the more reactions can occur
   2. sharp corners have lots of surface area
      a) weather quickly
      b) called spheroidal weathering

V. Metamorphism
A. definition
   1. alteration of existing rock to form another type of rock
      a) occurs in response to specific “agents”
         (1) heat
         (2) pressure
         (3) chemical activity
      b) weathering is decomposition, not metamorphism
   2. rock is formed under a given set of conditions
      a) agents change conditions
      b) rock is no longer at equilibrium
      c) minerals react to equilibrate with new conditions
   3. can be a simple transformation (shale to slate)
   4. can be so complex that it is impossible to determine what the original rock was

VI. Heat
A. probably the most significant metamorphic agent
B. heat energy is necessary to recrystallize existing minerals
   1. for example, clay is unstable at elevated temperature
   2. clay minerals tend to form mica
   3. mica becomes unstable at ye higher temperatures
C. sources of heat
   1. deep burial of surface rocks
      a) results from tectonic activity, mountain building
      b) T goes up 20-30 °C per kilometer of depth
   2. rising magma body
D. contact metamorphism
   1. most apparent when magma rises nearly to the surface
   2. produces an extreme temperature difference
      a) near surface country rock is cool
      b) temperature gradient creates a thin altered zone
      c) it is also likely that plenty of water is available
(1) assists in chemical reactions
(2) transfers heat rapidly

VII. Pressure
A. sources of pressure
   1. burial in a subsiding basin
      a) weight of the overlying material
   2. tectonic burial
      a) mountain building thickens the Earth's crust
   3. directional pressure
      a) induced through tectonic/igneous activity
B. effects of pressure
   1. compacts mineral grains
   2. recrystallization at contact points
   3. mineral grains become elongated
   4. rotate to become parallel
   5. remember that hot rocks under pressure are much more pliable than what we see at the surface

VIII. Chemical activity
A. fluids can react with minerals in the rock to form new minerals
   1. mostly water
   2. carry ions in solution
   3. my be acidic or caustic
   4. hot water is more reactive than cold
      a) carries ions easier than cold water
      b) higher energy levels
B. water comes from
   1. dehydration of minerals (clays)
   2. pore spaces between mineral grains
   3. seafloor spreading zones
   4. released from magma with other fluids and gases

IX. Metamorphic effects on texture
A. texture reflects the degree of metamorphism
   1. directed pressure leads to alignment of mineral grains
      a) elongate perpendicular to primary stress
      b) creates a banded structure referred to as foliation
   2. pressure and temperature cause recrystallization
      a) bigger crystals
      b) grow perpendicular to primary stress
B. slaty cleavage
   1. slate forms from shale under low-grade metamorphism
      a) relatively mild pressures and temperatures
b) clay minerals change to tiny mica crystals
   (1) too small to see
   (2) oriented perpendicular to principal stress
2. slate breaks parallel to the mica crystals
   a) called slaty cleavage,
   b) different than mineral cleavage
C. schistosity
   1. increased pressure and temperature
   2. forms larger (visible) mica crystals
   3. gives the rock a scaly appearance
   4. rocks are often deformed, wavy
D. gneissic texture
   1. occurs at highest temperatures (less than partial melting)
   2. minerals segregate
   3. form light and dark bands within the rock
   4. foliated but will not split along the foliations
E. nonfoliated texture
   1. crystals are of similar size in all directions
   2. usually occurs when a single mineral is present
      a) minor impurities can add color and form bands
      b) limestone metamorphoses into marble
      c) impurities can make spectacular patterns

X. Metamorphic effects on mineralogy
A. minerals change during metamorphism
   1. original ones not stable in the new environment
   2. form stable minerals for the changed environment
B. two basic categories of mineralogic changes
   1. new minerals form from existing minerals and in situ water
      a) some elements/compounds may leave (e.g., CO$_2$)
   2. new ions are added by hydrothermal fluids
      a) fluids released from a cooling magma
      b) sea water percolating near spreading sites
         (1) metal rich fluids gush from undersea springs
         (2) cold water leads to rapid precipitation
C. diagnostic (index) minerals
   1. indicative of particular environments
   2. can be used as diagnostic tools
   3. examples of index minerals
      a) chlorite (low temperature and pressure)
      b) garnet (high temperature)

XI. Categories of metamorphic processes
A. regional metamorphism
1. burial places pressure on large regions
2. temperature is elevated

B. contact metamorphism
1. magma ‘bakes’ or ‘boils’ the surrounding rocks
2. surrounds batholiths, dikes, sills

C. fault metamorphism
1. blocks of solid rock slide past each other
2. creates a highly deformed or pulverized zone
3. relatively rare occurrence

D. partial melting
1. this is rarely a metamorphic process
2. partial melting often forms new magma
   a) this is an igneous process, not metamorphic
   b) key factor is that the molten rock migrates
3. occasionally the molten rock stays in place
   a) some, but not all minerals melt then solidify
   b) this forms a metamorphic rock

E. combinations of the above

XII. Foliated metamorphic rocks
A. slate
1. very fine grained rock
2. composed mainly of small mica flakes
3. results from low grade metamorphosis of shale
4. usually red, black, green
   a) green comes from iron-silicate minerals
   b) red is hematite stain (iron oxide)
   c) black implies high organic content (petroleum)
5. foliation
   a) cannot be seen
   b) known to exist from strong cleavage
   c) results from alignment of mica flakes

B. phyllite
1. midway between schist and slate
2. looks like slate except the cleavage surfaces have a sheen
3. often green in color, with bright mica flakes

C. schist
1. strongly foliated rocks
2. formed by regional metamorphism (mountain building)
3. individual mineral grains are visible (platy)
4. rock can be split into flakes or slabs
5. foliations are often deformed
6. schist refers to the texture
7. mineralogic descriptors are added (e.g. garnet-mica schist)
8. often contain accessory minerals
   a) such as garnet, staurolite
   b) embedded within the platy structure

D. gneiss
1. banded metamorphic rocks
   a) alternating light-dark bands
   b) bands consist of elongated mineral grains rather than the platy mineral grains found in slate and schist
   c) banded structure can display intricate folding
2. results from high grade metamorphism,
3. gneiss refers to the texture
4. mineralogic descriptors are added (e.g., granite gneiss)

E. migmatites
1. transition between igneous and metamorphic rocks
2. low temperature minerals actually melt
   a) silicates such as quartz, potassium feldspar
   b) melted portion stays in place and recrystallizes in the banded form

F. mylonite
1. mineral grains are highly deformed and elongated
2. forms from shear stress in fault zones

XIII. Nonfoliated metamorphic rocks
A. quartzite
1. high grade metamorphism of sandstone
2. quartz grains fuse to form a very hard rock
B. marble
1. coarse grained crystalline rock
2. formed from the carbonate rocks (limestone, dolostone)
3. pure white marble is prized by sculptors,
4. impurities within marble can impart colors and patterns