Metamorphism and Metamorphic Rocks

Metamorphism is defined as the mineralogical and structural adjustment of solid rock to physical conditions different from original conditions of formation (exclude weathering and diagenesis) but conditions less rigorous than for melting. The term metamorphism comes from the Greek "meta" = change and "morph" = form, so metamorphism means to change form. These changes take place in the solid state (ie. there is no melting involved) but the reactions are often aided by the presence of fluids, typically in the form of a high density vapor phase along grain boundaries. Metamorphic rocks are classified primarily on the basis of texture. We will look at these different textures in the lab. Here we will focus primarily on how metamorphic rocks can provide an indication of the deformation history, as well as the temperature and pressure conditions under which metamorphism took place.

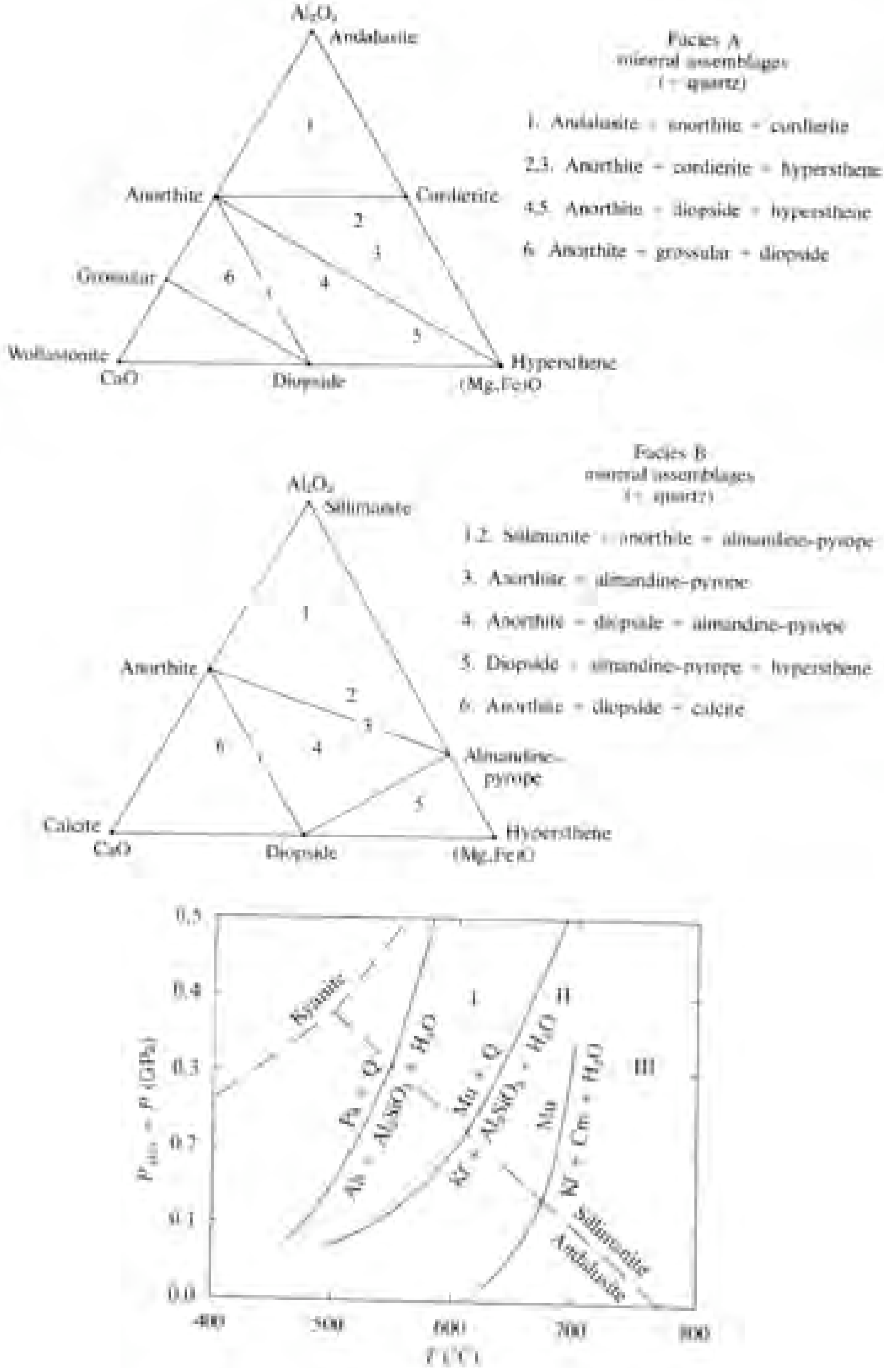
Types of metamorphism
- Contact (thermal)
  - recrystallization around intrusion
  - characterized by nonfoliated texture
- Regional
  - enhanced T and directed P associated with deformation
  - characterized by rocks with foliation
- Other types
  - Cataclastic (granulation in fault zone at low T,P)
  - Burial (normal T increase in thick section of volcanic or sedimentary rock)
  - Seafloor hydrothermal (characterized by circulation of hot fluids)

Classification of metamorphic rocks by texture
- Directed textures
  - foliation and/or compositional banding in response to directed P
  - slate => phyllite => schist => gneiss
- Nondirected textures
  - recrystallization in uniform stress field
  - examples include marble, quartzite, hornfels

Inferring P/T conditions of formation
- Brittle vs ductile behavior
- Orientation of foliation perpendicular to maximum compression
- Deformation stores energy in crystals
- Recrystallization (return to lower energy state)
- Calibrating P/T conditions
  - Index minerals
  - Metamorphic Facies

Metamorphic Facies and Tectonic Setting
- Contact metamorphism (low P and elevated T)
- Regional metamorphism in collision zones
- Subduction zone metamorphism

Why don't metamorphic assemblages revert to original state when exposed at surface?


Al_2O_3
Andalusite
Facies A
mineral assemblages
(+ quartz)
1. Andalusite + anorthite + cordierite
2,3. Anorthite + cordierite + hypersthene
4,5. Anorthite + diopside + hypersthene
6. Anorthite + grossular + diopside
Anorthite
Cordierite
Grossular
Wollastonite
CaO
Diopside
Hypersthene
(Mg,Fe)O
Facies B
mineral assemblages
(+ quartz)
Al_2O_3
Sillimanite
1,2. Sillimanite + anorthite + almandine-pyrope
3. Anorthite + almandine-pyrope
4. Anorthite + diopside + almandine-pyrope
5. Diopside + almandine-pyrope + hypersthene
6. Anorthite + diopside + calcite
Anorthite
Almandine-pyrope
Calcite
CaO
Diopside
Hypersthene
(Mg,Fe)O
0.5
0.4
0.3
0.2
0.1
0.0
400
500
600
700
800
$P_{H_2O} = P$ (GPa)
T (°C)
Kyanite
I
II
III
Pa + Q
$Ab + Al_2SiO_5 + H_2O$
Mu + Q
$Kf + Al_2SiO_5 + H_2O$
Mu
$Kf + Crn + H_2O$
Sillimanite
Andalusite

Lecture 11: Metamorphism (Classification, Processes) Oct. 16, 2006

What is metamorphism?

metamorphism = the mineralogical and structural adjustment of solid rock to physical conditions different from original conditions of formation (exclude weathering and diagenesis) but conditions less rigorous than for melting.

illustrate general boundaries on P/T diagram
- high temperature melting regime, T depends on presence of water (700-900°C)
- sedimentary regime, essentially at low T, low P corner
- exclude from metamorphism the processes of weathering and diagenesis
  - diagenesis = compaction, recrystallization, cementation

recrystallization in solid state (often aided by presence of dense fluid phase)
- new mineral phases (stable at new P/T) grow at expense of old phases
- or grain growth of existing phases if they remain stable

structural adjustments reflecting the new stress state
- if stress state is not uniform, then preferred orientation of mineral grains

In the strict sense, metamorphism is an isochemical process. Often aided by the presence of a high density fluid phase along grain boundaries. *Metasomatism* (changes in chemistry by introduction or loss of material), for example, with high water rock ratios.

What are the dominant controls on metamorphism?

1) Composition of starting material
- e.g. Q sandstone can only yield quartzite
- *protolith* - rock name prior to metamorphism

2) T, P conditions
- In general, P and T increase together.
  - metamorphic *grade* or intensity: low, medium, high
- instead of pressure, we generally refer to *stress* (which has connotation of direction)
  - pressure (scalar) is simply case when stress (force/area) is same in all directions

uniform = *hydrostatic* stress
- e.g. in a fluid, causes change in volume
- $P = \rho * g * h$

differential stress (above and beyond the uniform hydrostatic stress)
- general case stress in different directions is not equal
- normal stress, shear stress
- symmetric 2 rank tensor with eigenvalues $\sigma 1 > \sigma 2 > \sigma 3$ (dir. where shear = 0)
- causes changes in shape/volume

3) Presence of fluids
- speeds reactions
- sources of fluids
  - a) incorporated in rock pore spaces or fractures
  - b) hydrous minerals (micas, amph etc.) much more important source
    - metamorphic reactions often yield water as product (more about this later)

example: dry diffusion rate of K in feldspar @500°C 10^8 yr/cm
wet diffusion rate 10^2 yr/cm

4) Time
reactions not instantaneous
increase in grain size with time

Types of Metamorphism

1. *Contact* (thermal)
   recrystallization in halo shape around intrusion
   generally relatively small
   mm sized baked zones to several km
   distinguishing characteristic: *non-foliated* texture

2. *Regional* - thermal and dislocation (deformation) effects assoc with collision zones
   generally large area (100s - 1000s km^2)
   thermal effects related to geothermal gradient rather than intrusion
   deformation effects
   recrystallization
   distinguishing characteristic: *foliated* texture

3. Other types
   a. *Cataclastic*
   granulation in fault zone at low T,P (fault *gouge*)
   b. *Burial*
   thick sediment or volcanic accumulation
   normal geothermal gradient and no deformation
   c. *Seafloor or hydrothermal*
   metasomatism with high water/rock ratios
   water infiltrates into crust through fractures, heated and leaches out Fe,Ca etc.
   vents/plumes - hot fluids with Fe,Ca react with seawater >> gypsum, sulfides

Fabric types and classification

Classification based on texture and mineralogy

Directed textures (regional)
foliation = planar texture (anisotropic minerals and/or compositional banding)
can and often does cut across original layering

example with clay rich rocks (increase in grain size, alignment)
shale
slate - surface lustery (*slaty cleavage* = alignment of tiny mica grains)
phyllite - grains just visible
schist - visible grains
gneiss - banding of minerals (mm to cm scale)

Nondirected textures (isotropic)
recrystallization in uniform stress field
increase in grain size
increase in degree of interlocking grains

marble
quartzite
hornfels - very fine grained rocks from contact metamorphism
granulite - very coarse grained (Q,Kspar,Pyrox), no hydrous phases