GY 111 Lecture Notes
Intro to Metamorphism

Lecture Goals:
A) Agents of Metamorphism
B) Types of metamorphism
C) Hydrothermal fluids

Reference: Press et al., 2004, Chapter 9; Grotzinger et al., 2007, Chapter 6

A) Agents of Metamorphism

The term metamorphism means to change a rock (commonly called the parent rock) from its original composition (e.g., a shale or a basalt) to something new (e.g., a metamorphic rock). The cause of these changes are the so called "agents of metamorphism." The first time that I heard the term "Agents of Metamorphism", I thought it would make a great name for a punk rock band\(^1\). Now I know better; the AOM is a better name for a classic rock group. Bad music not withstanding, there are three true agents of metamorphism:

1. **Heat** (25°C to 800°C; up to the point of melting)
2. **Pressure** (1 Bar to 12,000 Bars)
3. Chemically active fluids\(^2\) (AKA hot water)

Each can single-handedly induce metamorphism in rocks, or they can act collectively. Heat is associated with one of two tectonic situations. The first is with proximity to intrusions like plutons, batholiths or laccoliths. The country rock that is in direct contact with these hot bodies experiences the highest temperatures. The further away that you get from the pluton, the lower the temperature. In this tectonic setting, the highest grade heat-only (or thermal) metamorphism is in direct contact with the intrusion. Lower grade heat-only metamorphism occurs further into the country rock. Areas of equal temperature that surround the intrusion are called isotherms and they more or less delineate the extent of heat-only metamorphism within the country rock. Because this type of metamorphism only occurs in contact with intrusions, it is usually called **contact metamorphism**. Good

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\(^1\) The band that we had in my geology class was actually called Johnny Oolite and the Void Spaces. True story. Most geology classes have a "band" and most geology bands have geologically-inspired names. Like most university groups, Johnny and the boys kind of sucked.

\(^2\) Another great name for a rock band.
name huh? The area of metamorphism around the intrusion is frequently called a contact metamorphic aureole.

The other tectonic setting where heat can induce metamorphic changes is through burial. It is well known that the deeper you go in the Earth's interior, the hotter it gets. The rate of increase is called the geothermal gradient and although highly variable depending upon proximity to active plate boundaries, it averages about 25 -30°C/1000m. So about 10 km down, the temperature of the rocks is 300°C hotter than it would be at the surface. The deep you go the hotter it gets and by the time you are at the base of the lithosphere, it’s really quite toastie. By the way, at these depths, it is impossible to separate out the pressure component from the temperature component of metamorphism.

Pressure is a metamorphic agent that requires a bit of explanation. We kind of touched on pressure when we were discussing lithification in one of our sedimentation lectures. Compaction is a type of horizontal pressure that occurs when muddy sediment is dewatered during shallow burial. That type of pressure occurs when more sediment is deposited on top of the wet mud. The overburden squeezes the water out of the mud ultimately converting it into shale. The pressure associated with metamorphism is far more extreme than compaction. Moreover, it need not be horizontal. Metamorphic pressure is best described as stress because it is directed. Think of a mechanical press that is free to rotate on any axis. Pressure like this can occur during burial, but the most extreme examples of stress are usually associated with convergent plate boundaries.
In the same way that isotherms delineate areas of equal pressure around intrusions, isobars delineate areas of equal pressure at these plate boundaries. The highest grade pressure-induced metamorphism takes place close to the boundary. The further you move away from there (in either direction), the lower the pressure becomes and the lower the grade of pressure-induced metamorphism. At convergent plate boundaries, heat increases with depth so isotherms must also be factored into the metamorphic grade.

The role of chemically active fluids will be discussed separately at the end of the next section.

**B) Types of metamorphism**

So, we have discussed the role of heat and pressure in metamorphism and touched on the importance of plate tectonics in the generation of metamorphic rocks. Now it is time to piece it all together.

Contact metamorphism occurs adjacent to intrusions, and it can occur anywhere that a pluton occurs (e.g., divergent and convergent plate boundaries).

Compressive stress occurs with burial, but it is most intensive along convergent plate boundaries where mountain belts are forming. Since mountains are major regional phenomenon, this type of metamorphism is called **regional**. As a general rule, contact metamorphism involves only heat and regional metamorphism involves heat and pressure. The amount of heat and pressure depends upon where you are along the convergent plate boundary (see above diagram). If you are near the actual boundary at the top of the lithosphere (e.g., just below the trench), the metamorphism is dominantly high grade, pressure only. At depth, the metamorphism is high grade pressure and heat.

Since we are talking about pressure and temperature as agents of metamorphism in a plate tectonic setting, it would be best at this point to discuss situations of high stress...
involving **shear**. When rocks are squeezed, sometimes they break along planes called **fractures**. If there is movement along the fractures, they are called **faults**. We will spend considerable amounts of time later in this course discussing how and why faulting occurs. For now, just consider how much shear stress the rocks experience along faults. It is frequently enough to induce major changes in mineralogy. This is another variety of contact metamorphism that is essentially, pressure-only induced. It is called **cataclastic metamorphism** to distinguish it from the heat only (contact) and heat+pressure (regional) varieties.

**C) Hydrothermal metamorphism**

So what about this "chemically active fluids" component of the metamorphic agents? In a tectonically active region where plutons and compressive stress are common, underground water can get hot. Very hot. Under pressure, this **hydrothermal water** can greatly exceed its normal boiling point. It can reach more than 400°C and still remain fluid. At these temperatures, water is capable of dissolving a lot of normally insoluble minerals. Quartz, and clays are easily dissolved as are important economic minerals like sphalerite, galena, chalcopyrite, and gold. The water tends to flow along fractures (the cracks are easy pathways) and tries to flow from high pressure regions to low pressure regions. Normally, this means that the water flows upward. When it rises to a shallow enough depth, the pressure decrease, the water flashes to steam and minerals start to precipitate out (see image to right of a **geyser**. Note the white precipitate at the base of the
geyser. This is **sinter**, a rapidly precipitated type of silica. If this water flashing to steam process sounds familiar it’s because it is how geysers like Old Faithful in Yellowstone National Park work. Below the park this very minute, hot water is precipitating quartz and inducing **hydrothermal metamorphism**. There might even be some gold mineralization taking place. Some geologists have even suggested mining the ancient geyser deposits in the park to find this valuable mineral. They are idiots. You **never** destroy elements in a nation park just to get rich fast. Some things need to be protected at all costs, even if it means that we lose out on some resources. Think of this when they start extracting oil from the Alaska National Wildlife Preserve sometime over the next couple of years. In order to keep all of the Hummers fueled up and on the road, quite a few caribou will be end up be exterminated. I may be a geologist, but I am also an environmentalist. Most geologists are. After all, who knows the Earth and what it can take before it completely falls apart better than us?

Anyway, I digress. I end this lecture with two **economic geology**-related diagrams. The first pictured above is from http://www.chesapeakegold.com and shows how gold/copper can be associated with hydrothermal systems (or as they say here, volcanic hydrothermal...
The second, to the left, is what it’s all about (at least as far as economic geology is concerned). Gold. The west was first settled because of it. Miners have gone “crazy over it”. We’ve even fought wars over it. All for a bit of shiny metal. The world will never have enough gold which is yet another reason why geology is a choice profession.

Important terms/concepts from today’s lecture

(Google any terms that you are not familiar with)

Parent Rock
Country Rock
Metamorphism
High Grade/Low Grade
heat
pressure
isotherms
isograds
contact metamorphism
regional metamorphism
cataclastic metamorphism
contact metamorphic aureole
burial
geothermal gradient
overburden
stress
shear
fractures
faults
hydrothermal water

geyser
sinter
gold
economic geology