Metamorphism & Metamorphic Rocks

Because the Earth is a dynamic system, rocks, once formed, may be subjected to very different conditions.

Metamorphism means Change

- Changes in conditions cause changes in mineralogy and texture of rocks.
- Because minerals that were stable at original conditions are no longer stable at new conditions.
- Changes that take place in the solid state between diagenesis (lower limit) and melting (upper limit) are called metamorphism.

Diagenesis vs. Metamorphism

- Gradational boundary.
- Metamorphism begins with the formation of new minerals not observed in any sediments at Earth’s surface.
  - (muscovite, chlorite, epidote, albite, paragonite, pyrophyllite)
- Diagenesis/Metamorphism boundary is at about 150°-200°C (~2 kilobars, but P is not critical).

Metamorphic - Igneous boundary.
• When metamorphic temperature gets very high, the rocks begin to melt
• Partly melted rocks are called migmatites (mixed rocks) and are considered metamorphic; melting T depends on rock composition
• granite and shale begin to melt at ~650°C
• basalts begin melting at ~800°C
• liquid+solid mixture for >200° T range
• If a rock gets mostly or completely melted, it is considered igneous

Protolith

• Any rock can be changed to become metamorphic
• Rock from which a metamorphic rock is formed is called its protolith
• Igneous protolith is indicated by the prefix "ortho-" (metaigneous)
• Sedimentary protolith is indicated by prefix "para-" (metasedimentary)
• Protolith is indicated by rock composition, inherited textures, often it’s hard to determine

Textures Characteristic of Metamorphic Rocks

• Deformation causes anisotropic fabrics
• foliation - any planar texture or structure in a rock
• schistosity - alignment of platy minerals (thin, flaky layers)
• gneissosity - mineral segregation (thicker layers)
- lineation - alignment of elongate minerals
- Metamorphic rocks are commonly folded
- They commonly contain porphyroblasts

Agents of Change in Metamorphism

- Mainly temperature (T) and pressure (P)
- Both temperature and pressure increase with depth in the Earth
- The rate of increase of temperature with depth in the Earth is called the geothermal gradient
- The geothermal gradient varies with tectonic setting

Continental Shield vs. Oceanic geotherm

Lithostatic (Load) Pressure increases with Depth

- \[ P = \rho gh \]
- \( \rho \) (density) \~ 3.0 g/cm\(^3\)
- \( g = 981 \text{ cm/sec}^2 \sim 10^3 \text{ cm/sec}^2 \)
- \( h = 1 \text{ km} = 10^5 \text{ cm} \)
- \( \Delta P / \text{kilometer} \sim 3 \times 10^5 \times 10^5 \text{ dynes/cm}^2 = \)
- \( 3 \times 10^8 \text{ dynes/cm}^2 \) (convert to bars pressure)
- \( \Delta P / \text{kilometer} \sim 300 \text{ bars/km} \text{ or} 0.3 \text{ kilobars/km} \)
- 1,000 bars = 1 kilobar \~ 3.3 \text{ kilometers depth}
Burial metamorphism - at the base of a thick sedimentary sequence, very low grade ($T_{max} \sim 300^\circ$C, garnet grade) metamorphic conditions may be reached.

Contact metamorphism - heat from a pluton may raise T of country rocks high enough to cause metamorphism (growth of new metamorphic minerals).

Regional metamorphism - crustal scale thrusting, caused by continental collisions, exposes rocks to high pressures and temperatures to cause regional metamorphism.

Subduction zone metamorphism - when cold rocks are dragged down into a subduction zone, temperatures are lower than normal for a given depth.

Define Isograd

- An isograd is a line on a map marking the first appearance of a new metamorphic mineral.
- Defined by Barrow in 1890s.
- Interpreted to be a line of approximately equal metamorphic grade (or T and P during metamorphism).

Characteristics of Contact Metamorphism

- Metamorphic effects are localized around a pluton; obvious association with a pluton.
- Isograds are approximately concentric with pluton margin (form contact aureole).
- Very limited extent; at most a few km wide.
- Mineralogic changes reflect mostly changes in T.
- Minerals are mostly low pressure minerals.
• Minerals lack preferred orientation, rocks are generally undeformed (called hornfels)

Contact Metamorphism of impure Limestone

Characteristics of Regional Metamorphism

• Metamorphic effects are not clearly associated with a pluton
• Effects are regional; extending over 10s to 100s of kilometers
• Rocks contain moderate to high pressure minerals. Like what?
• Rocks are generally deformed and have strong fabrics (lineation and foliation)
• Mineral changes reflect changes in both T and P

Regional Metamorphism in Scottish Highlands (see handout)

The Great Glen Fault

Intermediate Cases between Contact and Regional Metamorphism are Common (Low Pressure Regional or Regional/Contact Metamorphism)

Mineralogic Changes depend on original rock composition, because ingredients needed to make minerals must be present in the protolith

• Quartz crystals in a quartz arenite just get bigger (recrystallize), nothing else can grow- Ss becomes quartzite
• Pure calcite limestone becomes pure calcite marble
• Basalts form plagioclase, amphiboles and other mafic minerals

• Shales form aluminous minerals like garnet, biotite, muscovite, staurolite, Ky/And/Sill (and quartz)

Barrow (1893) was the first to show progressive changes in a single rock type and relate them to an increase in metamorphic intensity (grade)

• Metamorphosed shales (pelitic rocks)

• Dalradian Series in the Scottish Highlands

• Between the Great Glen Fault and the Highland Boundary Fault

• Defined isograd

Metamorphism in Scottish Highlands (see handout)