BSc (IV) semester: Lecture Notes (Prof. S. Sensarma)

Metamorphic Petrology

Metamorphism of rocks: Definition

Metamorphism is the process of changes in rocks, whereby originally formed igneous or sedimentary rock is changed in response to new conditions (e.g., higher P, T) to produce a metamorphic rock. Thus, for example, a granite (igneous rock) may change over to granite gneiss (a metamorphic rock). During meatmorpsim the original rock may change its mineralogy (phase changes) or structures (including textures) or both. However, most of the metamorphic rocks retain some of the characteristics of the original rock (protolith), such as bulk chemical composition, or gross features (e.g., bedding in sedimentary rock) while developing new textures and/or new minerals. The salient points of metamorphism of rocks may thus include:

1. It is essentially a solid to solid change. Recrystallization of pre-existing rocks (igneous or sedimentary) to an equilibrium assemblage of minerals and/or textures. A metamorphic rock may later be metamorphosed to as well.

2. Requires presence of elevated Temperature (<200°-800°C) and Pressure (2- >10 kbar)

3. Requires presence of fluid (e.g., H_2O, CO_2, CH_4 most common)

4. high Temperature range of metamorphism may transition onto partial melting of the rock (i. e, metamorphism transition into magmatic processes, i,e, domain of igneous petrology)

ALL METAMORPHIC ROCKS WERE ONCE IGNEOUS OR SEDIMENTARY ROCKS

Controlling Factors of metamorphism

Temperature

Temperature (T°C) invariably increases with depth, and the rate of change in T with depth is known as the **geothermal gradient**. Geothermal gradient may usually vary between 15-30°C/km, but extreme gradients as low as 5°C/km to as high as 60°C/km do occur. Hear flow (hence T) is higher in continent than that in the older ocean basins (Fig. 1), but young oceanic crust experiences higher heat flow because it is still cooling from its original formation at magmatic temperatures.

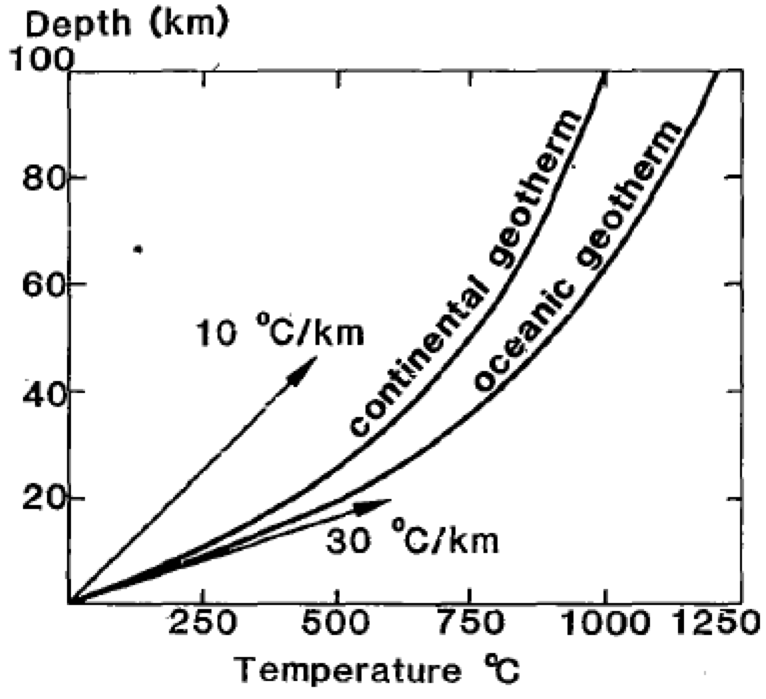

Fig. 1 Representative Geotherms in continental and oceanic regions (taken from Yardley, 1990)

The sources of heat are mainly three: (a) heat flowing into the base of the crust from mantle, (ii) heat generated by radioactive decay within the crust (greater in continental crust than in oceanic crust) and (c) heat brought into the crust by rising magma. The fourth factor is the effect of rapid uplift and erosion, crustal stretching that help bring hotter rocks to the near surface rapidly, without much loss of heat. As a result, there could be a steep temperature gradient and high heat flow, near to the surface in the areas experiencing regional uplift and concomitant large scale erosion

Pressure

Pressure (P) is a measure of force per unit area to which a rock is subjected to, and depends on the weight of the overlying rock, and hence depth. We generally use unit of pressure as bar or kilobar (kb). 1000 bar =1 kbar = 0.1 Gpa (gigapascal).

Lithostatic pressure at a point in the crust is the weight of the overlying rocks and is equal to ρgh, where ρ is the mean density of the overlying rock, h is the depth and g is acceleration due to gravity. During metamorpshim of rock, geologists assume that the pressure acting at a point is approximately uniform in all directions and equal to the lithostatic pressure. As a rough estimate, the pressure exerted by a 10 km rock column could be in the range of 2.6 to 3.2 kbar, depending on composition of the overlying rock. Lithostatic pressure is critical to evaluating the effects of pressure to stability of metamorphic minerals. Lithostatic pressure does not of itself cause deformation to the rock.

Deviatoric stress (directed pressure) is when the rock is subjected to different pressures in different directions. Deviatoric stress causes deformation to the rock as well. The deformation resulting from deviatoric stress plays a major role in determining textural characteristics of the rocks. The lateral pressures generated at much large scale (‘tectonic squeezing’) may be so higher than the lithostatic pressure that the mean presuure the rock is subjected to is significantly greater than the lithostatic pressure causing possible development of anomalously high pressure mineral assemblages at relatively shallow depths.

Fluid pressure: Another very important pressure variable during metamorphism of rock is fluid pressure**.** This is the pressure exterted by the fluid present in the pore spaces and along grain boundaries in the rock. Where rock is dry during metamorphism, fluid pressure is effectively zero, and lithostatic pressure acts across the grain boundaries, holding the grains together and make failure (deformation) difficult. On the other hand, if fluid is present and fluid pressure tends to act in the opposite direction, reducing the effective pressure across the grain boundaries, fracturing become more likely. If fluid pressure exceeds lithostatic pressure by more than tensile strength of the rock, the rock is likely to brust due to hydraulic fracturing and thereby fluid may escape along cracks. However, in metamorphic rocks fluid pressure drops low to very low because of small amount of pore fluid remaining is rapidly absorbed by mineralogical reactions (phase changes) that took place during metamorphism.

Types of metamorphism

On the basis of predominance of different factor or combination of factors responsible during metamorphism (as explained above), several types of metamporphism are identified:

Regional metamorphism takes place by both elevated pressure and temperature over large areas (hundreds to thousands of square km) and give rise to metamorphic rocks over large areas characteristics of many mountain chains. In this type of metamorphism, however, rise in temperature (heating) occurs without a close association with igneous bodies, although intrusions may contribute to the overall rise of temperatures. This type of metamorphism is almost invariably accompanied by deformation and folding. Regional metamorphic rocks develop planar fabric (e.g., schistosity, gnisiosity) because of directed stress.

Burial metamorphism is a form of regional metamorphism that may take place when a very thick sedimentary rock succession develops in a subsiding basin, so that low temperature metamorphic conditions are attained at the base of the pile of sediments without any accompanying deformation and folding typical of regional metamorphism.

Contact or Thermal metamorphism is the type of metamorphism that results from rise in temperature in cold surrounding the country rock by intruded magma that produce a contact metamorphic aureole. The aureole rocks are not deformed during metamorphic recrystallization and grains grow together in an interlocking manner to form a tough rock in the contact, known as **hornfels**. However, it is possible that vestiges of structures of the country rocks (protolith) may be retained, while in some cases deformation may accompany the igneous intrusions. This type of metamorphism is commonly encountered around granite plutons with its surrounding country rocks in the upper or middle crust.

Dynamic or cataclastic metamorphism: This type of metamorphism takes place because of deviatoric stress along fault planes or shear zones in the vicinity about zone of movement. Grain size reduction often takes place because of mechanical comminuation (grinding), accompanied by recrytallization and/or by growth of hydrous minerals due to movement of fluid along these fault/shear zones. Mylonites are typical products of this type of metamorphism.

Hydrothernal metamorphism involves chemical changes (often called metasomatism) is the result of the circulation of hot fluid (e.g. H_2O) through a body of rock along fractures/cracks. This type of metamorphism is often associated with high level igneous activity that drives fluid circulation. Most widespread type of hydrothermal metamorphism is sea floor metamorphism that takes place at Mid-Oceanic Ridges (MOR).

Impact or Shock metamorphism takes place because of sudden increase in pressure in the existing rock, for example, at the point/area of intense seismic events or by high velocity meteorite impacts on earth (and also other planetary surfaces). The relaxation of mineral lattices after the shock waves are passed causes a rise in temperature that may lead to melting and even vaporisation. One of the best known examples of impact metamorphism is at Meteor Crater, Arizona (USA).

Metamorphic grade

Metamorphic grade denotes the level of pressure and temperature involved in forming a particular metamorphic rock (Fig, 2). In other words, ***Metamorphic grade*** is a general term for describing the state of relative temperature and pressure conditions under which metamorphic rocks form. As the temperature and/or pressure increases during metamorphism, rock is said to have undergone *prograde metamorphism* or that the grade of metamorphism increases.

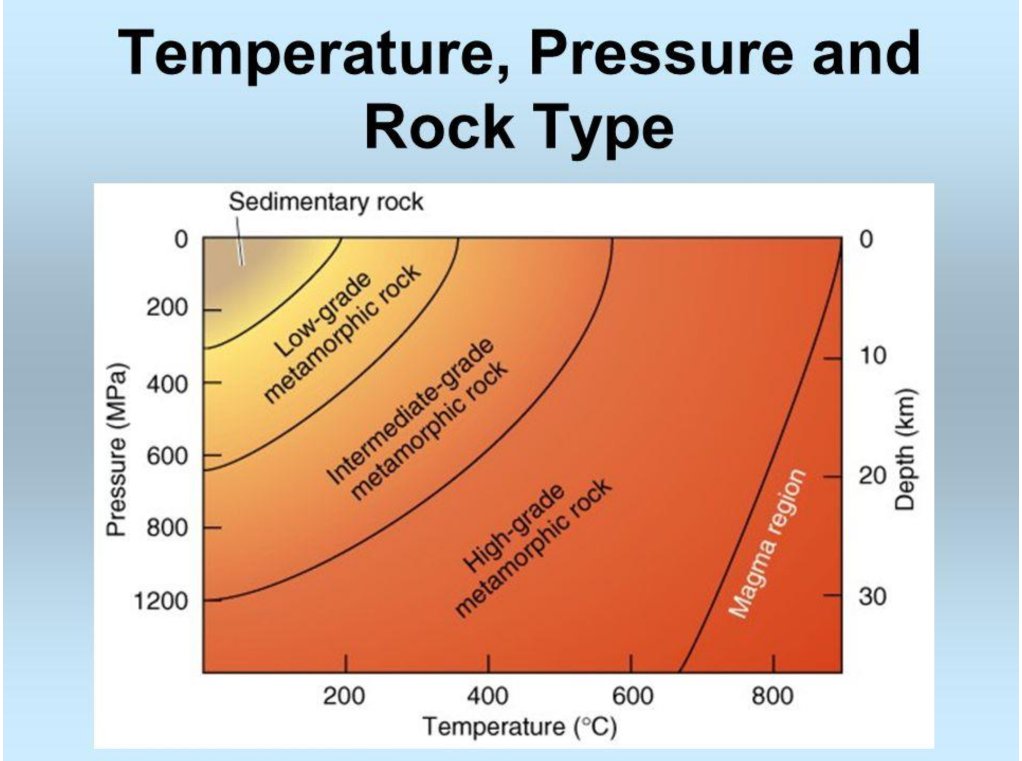

Fig. 2. Metamorphic grade increases with increasing P and T

Very low grade metamorphism occurs at a temperature below 200C. Lawsonite is a diagnostic mineral of very low grade metamorphism. Low grade metamorphism may take place between 200° and 320°C and at a relatively low pressure. In medium grade metamorphism temperature ranges between 400°C and 550°C. Pressure variations play an important role in determining the mineral stability formed in this grade. High grade metamorphism takes place at temperature greater than 600°-800°C and relatively at high pressure condition. High grade metamorphism generally takes place at a greater depth

Grade of metamorphism is identified in the field and under microscope on the basis of first appearance or disappearance of particular mineral(s), known as index minerals.

Follow next lecture *To be continued....*