Lecture Notes 12.001 Metamorphic rocks

O.Jagoutz

Metamorphism

Metamorphism describes the changes a rock undergoes with changing P, T and composition (X). For simplistic reasons we will focus here in the introduction dominantly on changes in P and T.

Why do we care?

Metamorphic rocks are important. We can measure the mineral compositions and assemblage (i.e. the different minerals preserved in a rock) and, knowing the chemical composition of the rocks we investigated we can use thermodynamic calculations to constrain the P-T conditions under which the rocks formed. As achievement of equilibrium requires rapid kinetics, which can be hard to achieve at lower temperatures, we can often determine multiple P-T conditions that a rock has undergone and from that construct what is called a P-T path. We will see later that we can combine these P-T constraints with radiogenic isotopic dating to construct P-T-t diagrams. Often we can further improve our understanding by adding diffusion modeling.

Because of all this, studies of metamorphic rocks can tell us a lot about the thermal state of the Earth in different geodynamic settings. We have already discussed that we think the earth is cooling down, which is one of the main aspects of planetary differentiation. The two most pronounced driving forces on Earth are gravity and heat. Gravity is essentially constant as the Earth's mass is now essentially constant. So since the end of the late heavy bombardment (4.1-3.8 Ga, a period of unusually intense asteroid bombardment) and probably even earlier, the main physical parameter that has changed on Earth through time is heat. This heat, together with gravity, essentially drives plate tectonics. It is possible that when the heat budget of the Earth was different early in its history that the Earth could have had a different stable regime other than plate tectonics. However, we have no clear record of the earliest Earth (the oldest rock is ~4.0 Ga), and when and how plate tectonics started is a major unsolved puzzle in Earth sciences.

What produces heat on earth?

We know from ~ 20.000 borehole measurements that the Earth continuously emits ~ 44TW

Leftover energy from the accretion of hot gases and dust contributes very little ~ 5-10 % (primordial heat)

Gravitational heat - The density sorting that resulted in the formation of the Earth's core released some energy, which can be considered another source of primordial heat.

Latent heat due to the crystallization of the Earth's core. The inner core grows by ~ 1 cm every 1000 yr, but this is a relatively minor heat source.

The most important heat source is from radioactive elements, mostly K, U and Th. Radioactive decay accounts for ~50-90% of the heat produced by the Earth, although the exact amount is poorly known. We can try to constrain the U, Th, and K concentrations by measuring geoneutrinos that are formed during radioactive decay. There is a gigantic program that monitors atomic explosions to see if other countries are testing nuclear weapons by measuring antineutrino fluxes (an atomic explosion produces an unusual spike in these). As a result we now know better the K, Th, and U concentrations in the Earth's mantle - a recent study suggested that it may only contribute ~ 50 % of the Earth heat budget.

Geotherm

The change in temperature with depth in the Earth is called the geotherm, which is different in different places.

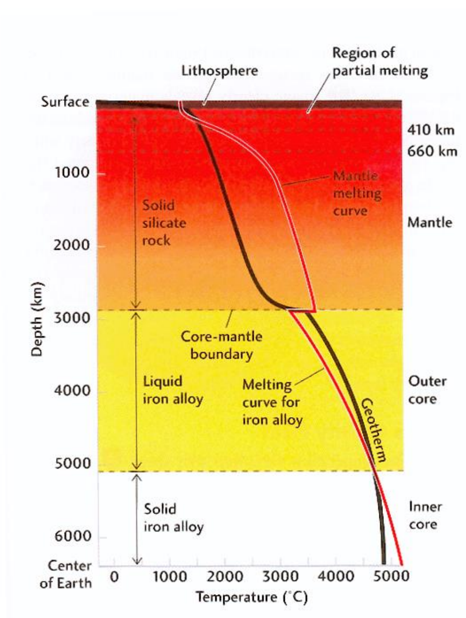
If heat is produced by radioactive decay we need to know the distribution of radioactive elements in the earth. Where are they? Crust, mantle, core? Quite a lot is in the crust but the mantle also contributes significantly. The geotherm can be mathematically described by a differential equation. Important is that in the lithosphere we have a conductive geotherm which is ~ 10-50°C/km, whereas in the upper mantle we have an adiabatic geotherm that is 0.5-1°C/km

Show geotherm for cold stable regions, average and hot extensional terranes.

Cold subduction zones ~ 5-20°C/km (for the uppermost 10km)

Normal crust ~30°C/km

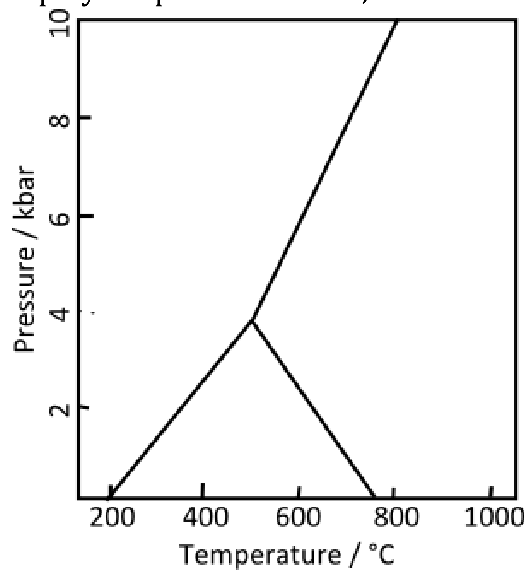
Hot mountain belts (thickened crust → more heat producing elements) ~50°C/km



When a rock is subject to changing P-T conditions, new minerals grow and existing ones become unstable and react to form new stable minerals.

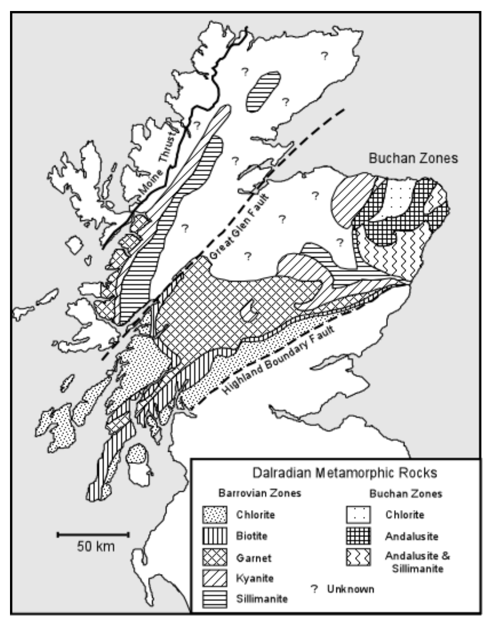
Aluminosilicates

Since we now understand something about the temperature regime in the Earth. we can discuss the effect of changing P and T on rocks. As an example, let's start with a simple system - Al_2SiO_5, the chemical formula for three different polymorphs: andalusite, sillimanite and kyanite



The stability of each polymorph is defined by a so-called discontinuous phase transition, the slope of which is defined as dP/dT=Cp/TdV (also known as the Clausius-Clapeyron relation). So reactions that have a large volume change are sensitive to pressure, whereas a small volume change accompanied by a large heat capacity change (you can also think of this as large entropy changes) is sensitive to temperature.

To understand metamorphic reactions in a broader context, it is best to consider rocks as a chemical system. Rocks have all kinds of variable chemical compositions, but traditionally metamorphism has been described for two main chemical rock types: basalts and pelites (mudstones/shales). Basalts are relatively Si-poor volcanic rocks such as those found on the ocean floor, while pelites are fine-grained sediments. The reason these have been studied a lot is because their compositions result in the formation and disappearance of lots of different minerals over a range of P-T conditions, making them both easy to identify and useful for determining P-T conditions in rock units.



This map is in the public domain.

The classic study of the metamorphism of basalts was conducted on Norwegian rocks by Eskola in the early 20th century. The two traditional areas where regional metamorphism of pelites has been described are Scotland and New England. In 1893, a guy called Barrow mapped the rocks in the Scottish highlands and he noticed the appearance of new minerals when he walked along. He found a characteristic set of zones defined by the appearance of minerals from Chlorite to Sillimanite, which we now know reflects changes in P-T conditions. Associated with the changing mineral assemblage he also found a textural changes, from slates through phyllites, schists and gneisses.

The boundaries for Barrow's zones are defined by the first appearance of a particular mineral, called an index mineral, which is characteristic of the zone. These boundaries were later called isograds (equal metamorphic grade).

Mineral Assemblages in Pelitic Rocks of each zone

Chlorite (slates & phyllites) - quartz, chlorite, muscovite, albite

Biotite (phyllites & schists) - biotite begins to replace chlorite, quartz, muscovite, albite

Garnet (phyllites and schists) - quartz, muscovite, biotite, almandine, albite

Staurolite (schists) - quartz, biotite, muscovite, almandine, staurolite, oligoclase

Kyanite (schists) - quartz, biotite, muscovite, oligoclase, almandine, kyanite

Sillimanite (schists & gneisses) - quartz, biotite, muscovite, oligoclase, almandine, sillimanite

The characteristic mineral assemblage of a rock at increasing P-T grade depends on the bulk chemistry of the rocks. The area was subsequently remapped by Wiseman (1934), who focused on the meta-basic rocks. He, like Eskola in Norway, realized that the mineral assemblages found in the basaltic rocks differed from those in the pelitic system. Depending on the conditions in metabasic rocks we talk about different *facies*. At low grade, rocks are dominated by green minerals (e.g. chlorite, actinolite, epidote etc) and are generally green = greenshist facies. Black amphibole-dominated rocks = amphibolite facies etc. blue amphibole dominated rock blueshist facies.

As a result we have now 3 different schemes to describe metamorphic conditions in rocks: facies, textures, and zones…. Good luck!