EENS 2120	Petrology
Prof. Stephen A. Nelson	Tulane University

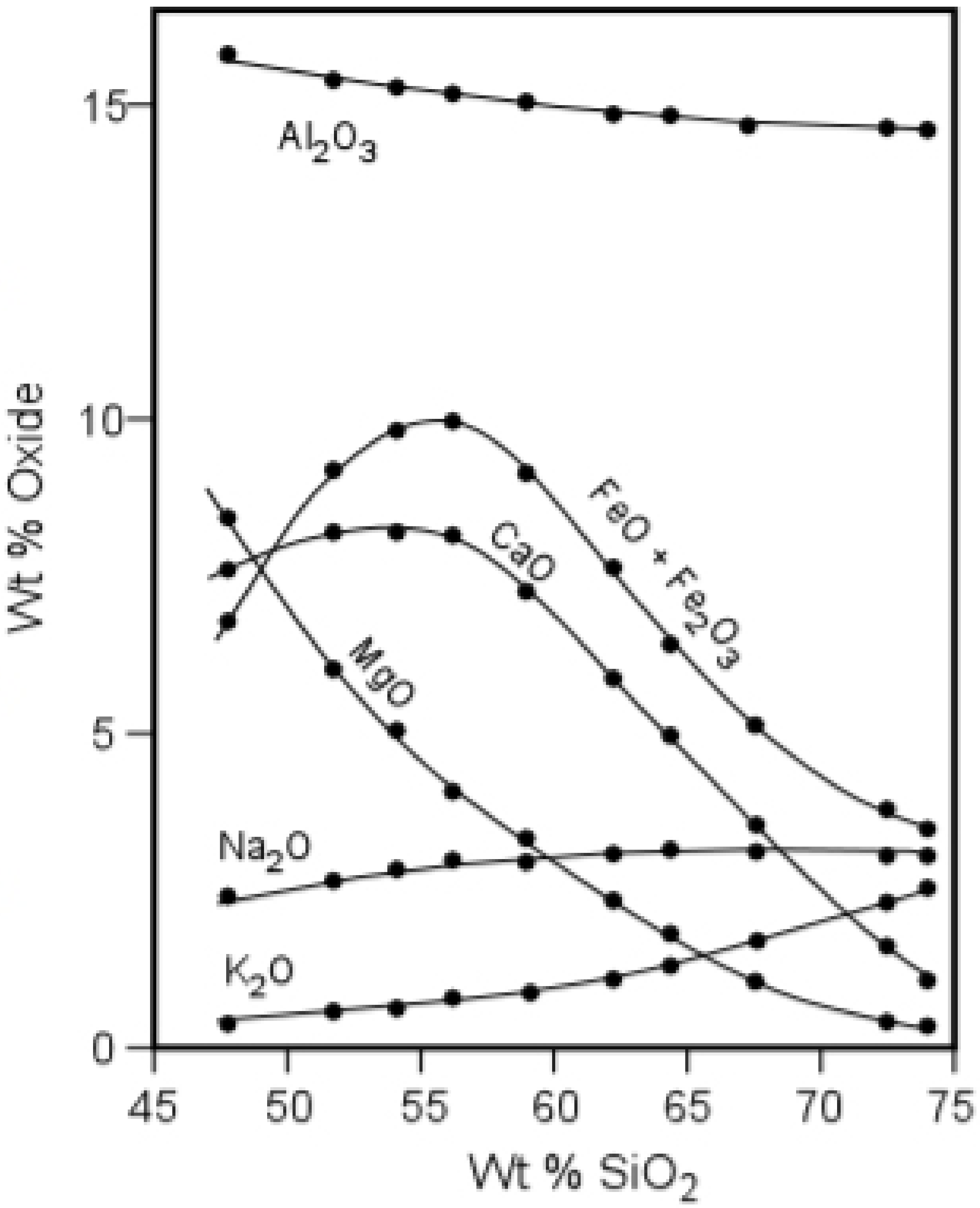
Magmatic Differentiation

This document last updated on 30-Jan-2012

Chemical Variation in Rock Suites

Soon after geologists began doing chemical analyses of igneous rocks they realized that rocks emplaced in any given restricted area during a short amount of geologic time were likely related to the same magmatic event. Evidence for some kind of relationship between the rocks, and therefore between the magmas that cooled to form the rocks came from plotting variation diagrams.

A variation diagram is a plot showing how each oxide component in a rock varies with some other oxide component. Because SiO_2 usually shows the most variation in any given suite of rocks, most variation diagrams plot the other oxides against SiO_2 as shown in the diagram here, although any other oxide could be chosen for plotting on the x-axis. Plots that show relatively smooth trends of variation of the components suggested that the rocks might be related to one another through some process. Of course, in order for the magmas to be related to one another, they must also have been intruded or erupted within a reasonable range of time. Plotting rocks of Precambrian age along with those of Tertiary age may show smooth variation, but it is unlikely that the magmas were related to one another.



If magmas are related to each other by some processes, that process would have to be one that causes magma composition to change. Any process that causes magma composition to change is called ***magmatic differentiation.*** Over the years, various process have been suggested to explain the variation of magma compositions observed within small regions. Among the processes are:

1. Distinct melting events from distinct sources.
2. Various degrees of partial melting from the same source.
3. Crystal fractionation.
4. Mixing of 2 or more magmas.
5. Assimilation/contamination of magmas by crustal rocks.
6. Liquid Immiscibility.

Initially, researchers attempted to show that one or the other of these process acted exclusively to cause magmatic differentiation. With historical perspective, we now realize that if any of them are possible, then any or all of these processes could act at the same time to produce chemical change, and thus combinations of these processes are possible. Still, we will look at each one in turn in the following discussion.

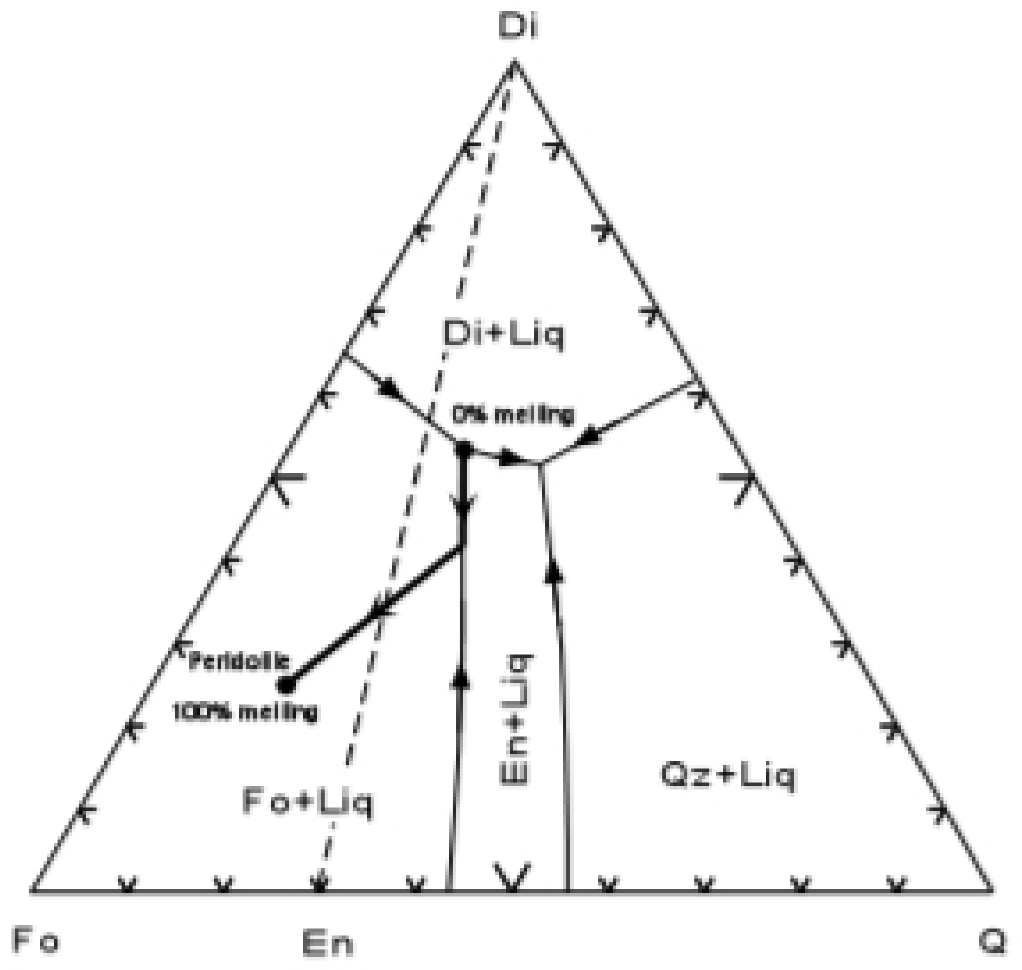
Distinct Melting Events

One possibility that always exists is that the magmas are not related except by some heating event that caused melting. In such a case each magma might represent melting of a different source rock at different times during the heating event. If this were the case, we might not expect the chemical analyses of the rocks produced to show smooth trends on variation diagrams. But, because variation diagrams are based on a closed set of numbers (chemical analyses add up to 100%), if the weight% of one component increases, then the weight percent of some other component must decrease. Thus, even in the event that the magmas are not related, SiO_2 could increase and MgO could decrease to produce a trend. The possibility of distinct melting events is not easy to prove or disprove.

Various Degrees of Partial Melting

We have seen in our study of simple phase diagrams that when a multicomponent rock system melts, unless it has the composition of the eutectic, it melts over a range of temperatures at any given pressure, and during this melting, the liquid composition changes. Thus, a wide variety of liquid compositions could be made by various degrees of partial melting of the same source rock.

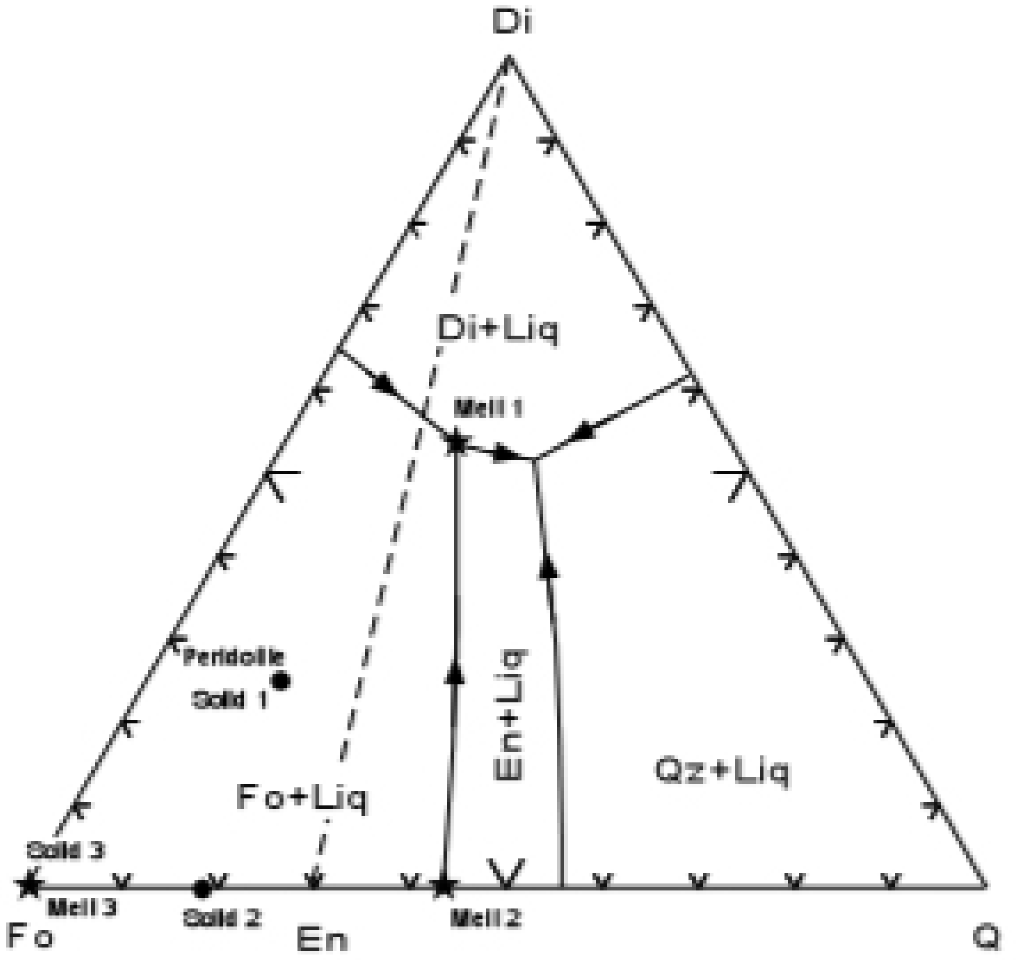
To see this, lets look at a simple example of a three component system containing natural minerals, the system Fo - Di - SiO_2, shown in simplified form here. A proxy for mantle peridotite, being a mixture of Ol, Cpx, and Opx would plot as shown in the diagram. This rock would begin to melt at the peritectic point, where Di, En, Ol, and Liquid are in equilibrium. The composition of the liquid would remain at the peritectic point (labeled 0% melting) until all of the diopside melted. This would occur after about 23% melting. The liquid would then take a path shown by the dark curve, first moving along the En - Ol boundary curve, until the enstatite was completely absorbed, then moving in a direct path toward the peridotite composition.



At 100% melting the liquid would have the composition of the initial peridotite. So long as some of the liquid is left behind, liquids can be extracted at any time during the melting event and have compositions anywhere along the dark like between 0% melting and 100% melting. (Note that the compositions between 0% melting and where the dark line intersects the En-Di join are SiO_2 oversaturated liquids, and those from this point up to 100% melting are SiO_2 undersaturated liquids).

Fractional Melting

Note that it was stated above that some of the liquid must be left behind. If all of the liquid is removed, then we have the case of fractional melting, which is somewhat different.



In fractional melting all of the liquid is removed at each stage of the process. Let's imagine that we melt the same peridotite again, removing liquids as they form. The first melt to form again will have a composition of the peritectic, labeled "Melt 1" in the diagram. Liquids of composition - Melt 1 can be produced and extracted until all of the Diopside is used up. At this point, there is no liquid, since it has been removed or fractionated, so the remaining solid consists only of Enstatite and Forsterite with composition "Solid 2". This is a two component system. Thus further melting cannot take place until the temperature is raised to the peritectic temperature in the two component system Fo-SiO_2.

Melting at this temperature produces a liquid of composition "Melt 2". Further melting and removal of this liquid, eventually results in all of the Enstatite being used up. At this point, all that is left in the rock is Forsterite. Forsterite melts at a much higher temperature, so further melting cannot take place until the temperature reaches the melting temperature of pure Forsterite. This liquid will have the same composition as pure Forsterite ("Melt 3").

We saw in our discussion of how magmas are generated that it is difficult enough to get the temperature in the Earth above the peridotite solidus, let alone to much higher temperatures. Thus, fractional melting is not very likely to occur in the Earth.

Trace Elements as Clues to Suites Produced by Various Degrees of Melting

Trace elements are elements that occur in low concentrations in rocks, usually less than 0.1 % (usually reported in units of parts per million, ppm). When considering the rocks in the mantle, trace elements can be divided into ***incompatible elements***, those that do not easily fit into the crystal structure of minerals in the mantle, and ***compatible elements***, those that do fit easily into the crystal structure of minerals in the mantle.

- Incompatible elements - these are elements like K, Rb, Cs, Ta, Nb, U, Th, Y, Hf, Zr, and the ***Rare Earth Elements*** (REE)- La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, & Lu. Most have a large ionic radius. Mantle minerals like olivine, pyroxene, spinel, & garnet do not have crystallographic sites for large ions.

- Compatible elements - these are elements like Ni, Cr, Co, V, and Sc, which have smaller ionic radii and fit more easily into crystallographic sites that normally accommodate Mg, and Fe.

When a mantle rock begins to melt, the incompatible elements will be ejected preferentially from the solid and enter the liquid. This is because if these elements are present in minerals in the rock, they will not be in energetically favorable sites in the crystals. Thus, a low degree melt of a mantle rock will have high concentrations of incompatible elements. As melting proceeds the concentration of these incompatible elements will decrease because (1) there will be less of them to enter the melt, and (2) their concentrations will become more and more diluted as other elements enter the melt. Thus, **incompatible element concentrations will decrease with increasing % melting.**