GY 111 Lecture Note Series
Crystallization of Magma and Lava

Lecture Goals
A) The chemical composition of the crust
B) Crystallization of molten rock
C) Bowen's Reaction Series

Reference: Press et al., 2004, Chapters 5 and 6; Grotzinger et al., 2007, Chapter 4

A) The chemical composition of the Earth:
In an earlier lecture, we discussed the nature of the interior of the Earth. Although it is unlikely that we will be able to visit the Earth's deep interior any time soon, we can still resolve chemical and mineralogical changes on the basis of seismic wave behavior. Volcanoes also give us some idea of the materials that compose the Earth's interior (after all, the lava that they erupt has to come from somewhere!).

So what exactly is the composition of the Earth's interior? It depends upon the depth that you are interested in. The mantle is different from the core and the core is different from the crust. Since we live on the crust, it is perhaps best to focus on this layer rather than others. At this point in our course, it is preferable not to use minerals as the basis of composition. They are too highly variable. Besides, there are two general types of crust anyway: 1) continental crust and 2) oceanic crust. Instead, we'll just look at the elemental composition of the Earth's crust. The following table lists the 8 most common elements (in weight percent and in % of atoms) of average crust:

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
<th>% of atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>46.6</td>
<td>60.5</td>
</tr>
<tr>
<td>Silicon</td>
<td>27.7</td>
<td>20.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8.1</td>
<td>6.2</td>
</tr>
<tr>
<td>Iron</td>
<td>5.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Calcium</td>
<td>3.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Sodium</td>
<td>2.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>All other elements</td>
<td>1.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>

If you ever wondered why quartz (SiO$_2$) is so common in crustal rocks or why there are so many different silicate minerals, these data should answer your questions. The more of a particular element that you have to work with, the more that element will form minerals. The equivalent
number of atoms is particularly useful for estimating mineral composition as it allows you to predict mineral formulas and hence mineral percentages.

Anyway, the gist of the matter is that the crust contains a lot of Si and O and there is a lot of SiO$_4^{4-}$ available for minerals. Now what we need to do is to discuss how these minerals actually grow in molten rock.

**B) Crystallization of molten rock**

Picture a container full of magma that you collected from a pluton deep in the Earth's interior:

As the magma starts to cool, it will start to grow crystals. This process is called **crystallization** and it is analogous to **precipitation** of crystals from solutions. Remember when you had to grow salt crystals in high school science class? You took salt, dissolved it in a glass of warm water and placed a string in the glass to act as a site of initial crystal growth or **nucleation**. The longer that you left the string in the solution, the bigger the crystals became. If you were impatient like me, you pulled the string out after a few minutes which was of course, too soon for any crystals to have formed. If you left the string alone for a day or so, crystals too small to be seen with the naked eye would have formed (**seed crystals**). Over time, layer after layer of salt is added to the seed crystals making bigger and bigger crystals. After a few weeks, you could see the cubic habit of halite. Crystallization of magma works the same way. Seed crystals form first and the crystals just get bigger and bigger and bigger. However, there are several **major** differences between crystallization of magma and precipitation of salt crystals. Not the least of which is that magma contains a combination of elements and subsequently will form many different minerals as it crystallizes. Salt water is pure and only forms halite as a precipitate.

Back to our jar of magma. Above 1800 degrees C, there are essentially no solid components to the melt. Everything is liquid. As the magma begins to cool, seed crystals of olivine begin to form. The chemical composition of olivine, at least according to your book, is (Mg,Fe)$_2$SiO$_4$. That olivine contains SiO$_4$ should come as no surprise to you. The cations are Mg and Fe. Any mineral that contains these two elements is called **ferromagnesium**. Ferromagnesium minerals tend to be the first to form from cooling magmas.

As crystallization continues, the olivine crystals get larger and large as layer upon layer is added to the seed crystals. The end result is a mineralogical version of the "Gob-stopper" candies that
you used to pop in your mouths. You know the ones; they were multi-layered. The longer you sucked them the stranger the colors became. The olivine crystals in cross-section look exactly like that:

![Diagram of olivine crystals with zonation](image)

You often see slight geochemical changes in the olivine crystals as they grow. They frequently start off Mg rich, but become more Fe rich over time. This is called **zonation.** It is necessary at this time to remind you that olivine is actually not a single mineral. We just treat it as one, but olivine is actually a mineral group. There are two end members, 1) Fayalite (Mg$_2$SiO$_4$) and 2) Forsterite (Fe$_2$SiO$_4$). In GY 111, we don't differentiate them, but magma crystallization often does:

![Diagram of olivine zonation](image)

As time goes on and the temperature begins to drop more and more, other minerals begin to crystallize out of the magma. At around 1100 degrees C, another ferromagnesium mineral forms. Pyroxene (chemical composition: Fe,Mg(SiO$_3$)$_2$) crystallizes along with olivine. This is an important concept. Crystallization of separate minerals is not sequential; they **overlap** one another. From time to time 3 or 4 or more minerals are all crystallizing at the same time.

Once minerals begin to form in a melt, they start to settle downward due to the influence of gravity. Minerals as solid substances tend to have higher specific gravities than the magma that they are crystallizing from. Hence they sink downward. The process is called **gravitational settling** (See adjacent sketch).

![Diagram of gravitational settling](image)

The scenario above will produce a lower layer enriched in olivine followed by a layer containing pyroxene and olivine. In the lab
component of the course, you will see examples of these rocks. The olivine-rich rock is called **Dunite**. The pyroxene-olivine-rich rock is called **peridotite**. As the magma continues to cool, different minerals start to form. The sequence that they crystallize out in is called the **Bowen's Reaction Series**. We'll get to that in a second. But first, a comment about what happens to the magma as crystals form.

The first two minerals to form from a cooling magma are olivine and pyroxene. Both of these minerals contain Mg, Fe, Si and O. As we discussed earlier, the Earth's crust is mostly composed of only 8 elements. Four of them combine to form olivine and pyroxene. As olivine and pyroxene crystallize, the relative percentage of Mg and Fe drop in the remaining magma because they are being removed by the minerals as they settle out of the melt. Simultaneously, the relative concentrations of Ca, Na, K and Al in the magma increase as olivine and pyroxene form. This effect is perhaps best illustrated by a bag of M&M's candies (today's lecture should come with a warning from the American Dental Association). Suppose you like red and green M&M's and selectively gobble them up from the bag. After a while, all of the red and green M&M's are gone and you are stuck with brown, yellow and whatever the rest of the colors are. Eventually, you have got to eat the brown ones to satisfy your lust for chocolate. Crystallization of magma works in the same way. After Mg and Fe is removed from the magma (red and green M&M's), other elements start to combine to form new minerals. This gradual change in magma composition is called **fractionation** or **fractional crystallization** and it is largely responsible for the mineral sequence comprising the Bowen's reaction series.

**C) Bowen's Reaction Series**

N. L. Bowen was a Canadian igneous mineralogist who conducted laboratory experiments on crystallization in the early to mid 1900s. A colleague of mine, now based at Harvard University, told me that Bowen uttered a very profound statement during a lecture by an rather arrogant geologist who claimed that he had seen most examples of igneous rocks all around the world and was therefore more qualified to hypothesize their formation than others who were lab-based. After the lecture, Bowen stated that he always felt that geologists should rely more on **insight than on sight**. I don't entirely agree with this, but we certainly have to think without preconceived ideas from time to time.

Bowen demonstrated that it was technically possible to produce a sequence of minerals from a **single magma source** through cooling and fractionation. The diagram to the right summarizes his work:

Geologists tend to divide the Bowen's reaction series into 4 components according to mineral composition. These divisions are used to subdivide the igneous rocks (**igneous rock composition**). The following table summarizes
the dominant mineralogy of the 4 igneous composition types:

<table>
<thead>
<tr>
<th>Composition</th>
<th>Formation Temperature</th>
<th>Dominant Minerals</th>
<th>Silica content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultramafic</td>
<td>Very high</td>
<td>Olivine, pyroxene</td>
<td>Very low (&lt;45%)</td>
</tr>
<tr>
<td>Mafic</td>
<td>High</td>
<td>Olivine, pyroxene, Ca-plagioclase</td>
<td>low</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Medium</td>
<td>Na-Plagioclase, amphibole, biotite</td>
<td>moderate</td>
</tr>
<tr>
<td>Felsic</td>
<td>Medium-low</td>
<td>Orthoclase, quartz, muscovite, biotite</td>
<td>high (&gt;65%)</td>
</tr>
</tbody>
</table>

Speaking of the labs, in order to conclude this lecture, it is necessary to consider some more stuff that we have (or will) be looking at in the lab component of the course. The igneous rocks are named in part by the minerals that they contain and in part by the texture those minerals form. The diagram below comes right from the lab manual and summarizes the textures that you will see in the rocks.

Important terms/concepts from today’s lecture
(Google any terms that you are not familiar with)

- Crystallization
- Precipitation
- Nucleation
- Seed crystals
- Zonation
Dunite  
Peridotite  
ferromagnesium  
gravitation settling  
fractionation (fractional crystallization)  
Bowen's reaction series (including the minerals)  
Continuous series  
Solid solution  
Igneous composition (ultramafic, mafic, intermediate, felsic)  
pumice, tuff, andesite, rhyolite