BOWEN'S REACTION SERIES

Frequently, people cannot visualize the mineral associations that form the sequences of igneous rocks that you find in the earth's crust and what happens to them once they are exposed at the earth's surface. Norman L. Bowen experimented with laboratory melts of igneous rocks and discovered an experimental crystallization sequence of minerals that matched what you can observe in nature. This sequence is called *Bowen's Reaction Series* and it includes most of the common rock forming minerals.

Background Information

Even in medieval times, miners realized that they could observe a sequence of mineral crystallization in rocks from early to late formed minerals. In the 1920's and 30's. Bowen ground up actual igneous rocks, along with mixtures of chemicals that could make up igneous rocks, and experimented with their melting relationships.

Bowen put the rock samples into what chemists call a "bomb," or a very strong enclosed sample holder, which can withstand very high temperatures and pressures without exploding. He would then heat them up until they melted (1600° C or more), and then cool them to a known temperature (i.e., 1400° C). He would hold them at that temperature long enough to allow crystals to start to form, and then he would throw the samples into a bucket of water to cool them instantly. This locked the minerals that had formed at the chosen temperature into the samples. Non-mineralized material would be glass. (What would this rock be called? ___________________)

When Bowen performed these experiments, he discovered that there was a regular mineral crystallization sequence exactly like the one that geologists observe in nature. He further found that there are two sequences of minerals, the discontinuous reaction series and the continuous reaction series. This can be seen in the Bowen's Reaction Series handout.

The Discontinuous Reaction Series

The left-hand side of Bowen's Reaction series are a group of mafic (or iron/magnesium-rich) minerals - olivine, pyroxene, amphibole, and biotite. As you go down Bowen's Reaction Series, the proportion of silica increases in the minerals' compositions. What this means in igneous magmas is that, if there is enough silica in the melt, each mineral will change to the next mineral lower in the series as the temperature drops.

In a basaltic melt, olivine will be the first mafic mineral to form. When the temperature is low enough to form pyroxene, all of the olivine will react with the melt to form pyroxene and pyroxene will crystallize out of the melt. This process is repeated at the crystallization temperature of amphibole, and then again at the crystallization temperature of biotite. Thus, one would think that all igneous rocks should only have biotite…but we know that it is not true. After olivine has crystallized, if there is not enough silica to form pyroxene, then the reaction will not occur and olivine will remain. Alternately, If you are crystallizing olivine and the temperature drops too fast for the reaction to take place (eg: the magma is erupted onto the surface by a volcano) then the reaction will not have time to occur, the rock will solidify quickly, and the mineral will remain olivine.
As you go down the discontinuous series, the structure of the silicates becomes more complex. Olivine forms isolated tetrahedral. Pyroxene forms single chain silicate. Amphibole forms a double chain. Biotite forms sheet silicates. The cooler temperatures allow for more complex minerals.

The Continuous Reaction Series

The right-hand side of Bowen's Reaction Series are the plagioclases. Plagioclase minerals have the formula $(Ca^{2+}, Na^{+})(Al^{3+}, Si^{4+})_3O_8$, or $NaAlSi_3O8$ – $CaAl_2Si_2O_8$. The highest temperature plagioclase has only calcium, while the lowest temperature plagioclase has only sodium. In between, these ions mix in a continuous series from 100% Ca and 0% Na at the highest temperature to 50% Ca and 50% Na at the middle temperature to 0 % Ca and 100% Na at the lowest temperature.

For example, in a basaltic melt, the first plagioclase to form might be 100% Ca and 0% Na plagioclase. As the temperature drops, the crystal would react with the melt and 99% Ca and 1% Na plagioclase would crystallize. Then those crystals would react to form 98% Ca and 2% Na feldspar, etc. All of this happens continuously, provided there is enough time for the reactions to take place and enough sodium, aluminum, and silica in the melt to form each new mineral.

The end result will be a rock with plagioclases with the same ratio of Ca to Na as the starting magma. On both sides of the reaction series, the silica content of the minerals increases as the crystallization trend heads downward. Biotite has more silica than olivine. Sodium plagioclase has more silica than calcium plagioclase.

Some examples of the use of Bowen's Reaction Series are:

1) From the top diagram, you can interpret the physical and chemical conditions under which a mineral crystallized. For example, olivine is a high temperature and pressure mineral with high iron and magnesium, and low silica.

2) The bottom diagram shows common rock names and their mineral associations. The minerals in each rock can be determined by looking horizontally across the diagram. For example, ‘basalt’ would have olivine, pyroxene and high calcium plagioclase, but would not have any quartz and potassium feldspar.

3) The top diagram shows mineral stabilities in a weathering environment. The least stable minerals are at the top of the diagram and the most stable at the bottom. Basalt contains olivine and calcium plagioclase. If it is being weathered, these minerals are very unstable and will readily break down by dissolving and forming clays, which are stable at 1 bar and 25° C. A granite contains quartz, potassium feldspar, and muscovite. The muscovite and potassium feldspar will break down, but the quartz is fairly resistant. When basalt and granite are weathered, eroded and deposited, you would expect to find lots of quartz, maybe some potassium feldspar and muscovite, but no olivine and calcium plagioclase.

4) The rocks (and their associated minerals) at the top and bottom of Bowen's Reaction Series should not occur in the same outcrop. The conditions that produce basalts are not the same as those that produce rhyolite. However, in cases where both rock types are present, they must have come from two different magmas (and probably at different times).

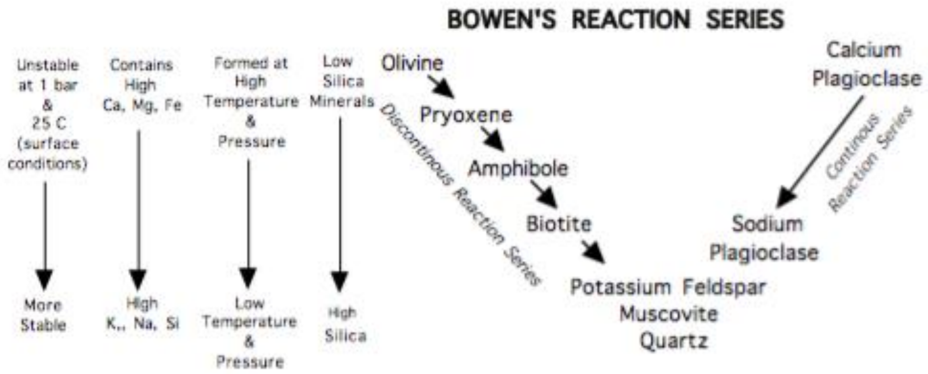
5) If a basalt has quartz in it (which occasionally occurs), the quartz must not have come from the magma itself, but from the rock into which the basalt intruded (melted) through.

6) The green and black beaches of the big island of Hawaii are made of grains of olivine and pyroxene (from the basalt lava flows that make up the island chain). According to Bowen's Reaction Series, these minerals should be unstable and should have weathered away. The calcium plagioclase has weathered quickly, but the olivine and pyroxene are a bit more resistant and have not yet had time to weather. While beach material can be made up of all different rock types, the less stable minerals wear away over time, leaving mainly just the more stable minerals. Therefore, most of the world’s beaches are made up of more resistant/stable quartz and feldspar - minerals found at the bottom of the diagram.

7) If a basalt magma cools slowly and quietly, the first minerals to form should be olivine and calcium plagioclase. These are solid crystals within the liquid melt. Since solids are generally more dense than liquids, the olivine and plagioclase will sink to the bottom of the magma chamber. Since olivine has a higher specific gravity than plagioclase, a layer of olivine will form at the bottom of a thick, quiet basalt intrusion.

8) A very large (1,000 km^3) and very deep (20 km) basalt intrusion will cool very slowly, giving you big crystals. The first minerals to crystallize will be olivine and calcium plagioclase. These will sink to the bottom. By being deposited at the bottom, they will be isolated from the melt and will not be able to react with it. When the melt reaches the right temperature for pyroxene and Ca-Na plagioclase, those minerals will crystallize and sink to the bottom and be isolated from the melt. Now you have a layer of olivine, a layer of Ca plagioclase, a layer of pyroxene, and a layer of Ca-Na plagioclase. Note that you are removing Fe, Mg, and Ca from the melt in this process, so the remaining magma must be relatively enriched in Na, K, and Si. The magma keeps crystallizing, so the next layers are amphibole and Na-Ca plagioclase, and then biotite and Na plagioclase. The remaining magma will be high in Na, K and Si and will crystallize as a granite. The original magma started crystallizing a gabbro, then a diorite, and finally a granite. Thus, just by the crystallizing order shown by Bowen's Reaction Series and the effects of gravity, a granitic magma can be made from a basaltic melt.

Physical Conditions and Bowen's Reaction Series



Igneous Rocks and Bowen's Reaction Series

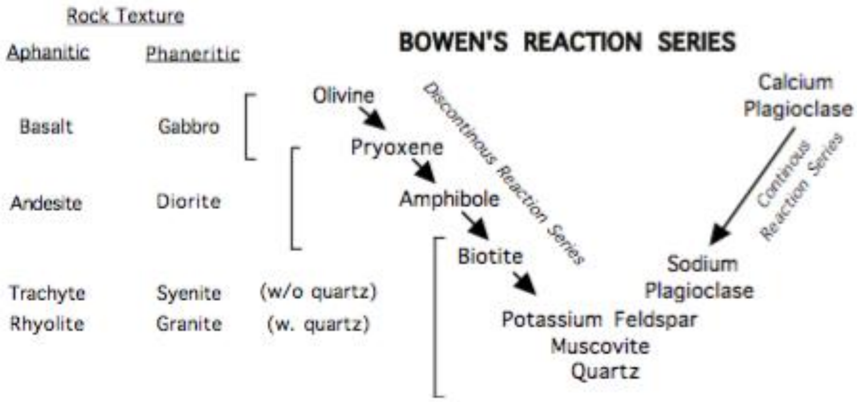
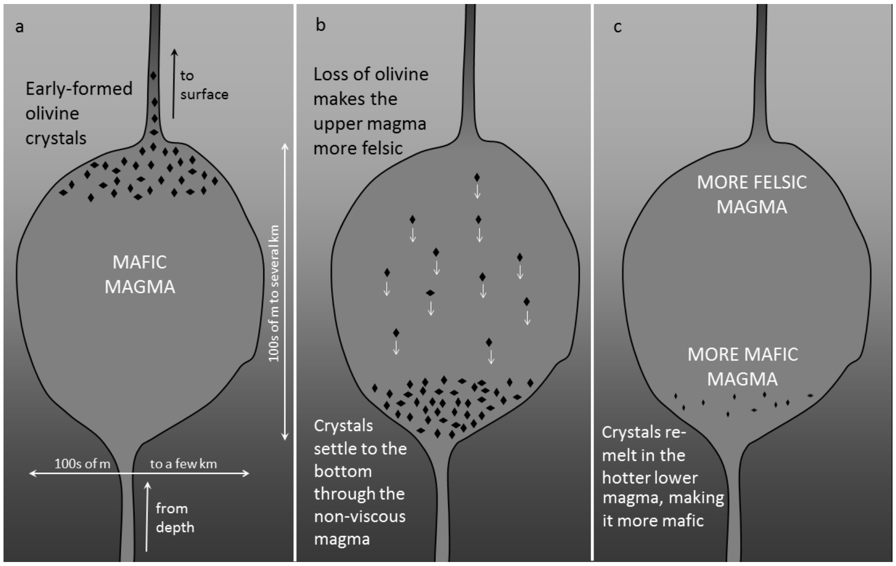


Figure 1. Bowen's Reaction Series



WORKSHEET

1) What minerals would you expect to find in the following rocks?

   Basalt:

   Diorite:

   Granite:

   Gabbro:

2) Why would you not expect to find olivine in a rhyolite?

3) You discover that a sample of basalt has quartz in it. Where did the quartz come from?