

BOWEN'S REACTION SERIES

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Purpose

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 in the 1920's and 30's, 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.

Definitions

Magma - molten igneous rock

Extrusion - magma extruded or placed on the surface of the earth to cool.

Intrusion - magma intruded or emplaced beneath the surface of the earth.

Feldspar - the family of minerals including microcline, orthoclase, and plagioclase.

Mafic - a mineral containing iron and magnesium

Aphanitic - mineral grains too small to be seen without a magnifying glass.

Phaneritic - mineral grains large enough to be seen without a magnifying glass.

Reaction Series - a series of minerals in which you mineral reacts to change to another

Rock Forming Mineral - the minerals commonly found in rocks. Bowen's Reaction Series lists all of the common ones in igneous rocks.

Specific Gravity - the relative mass or weight of a material compared to the mass or weight of an equal volume of water.

Teacher Information

Dating back to the earliest geology textbook, *De re Metallica*, written in medieval times, miners realized that they could observe a sequence of mineral crystallization in the rocks from early to late formed minerals. However, no relationship was codified previous to the work of Norman L. Bowen at the Carnegie Institute 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. He would put the samples into what chemists call a "bomb," or a very strong enclosed sample holder, which can withstand very high temperatures and pressures without exploding (although sometimes they do). He would heat them up until they melted, 1600^o C or more, then cool them to a known temperature, for example 1400^o C. He would hold them at that temperature long enough to allow crystal formation (minutes, hours or days) and then cool them immediately by throwing them into a bucket of water, thus locking into the samples the minerals that had formed at the chosen temperature. Non-mineralized material would be glass.

To find out what minerals, if any, had formed, he would analyze the samples with X-ray Diffraction. If there are minerals in the sample, X-rays will be diffracted, or bent, as they pass through the mineral. Glass causes no refraction. The angles to which the X-rays are bent are dependent upon the crystal structure of the mineral. Because every mineral has a different structure, every mineral has a different X-ray diffraction pattern. If there are no minerals in the sample, X-rays go straight through it without being diffracted.

When Bowen performed these experiments, he discovered that there was a regular mineral crystallization sequence exactly like the one that geologists observe in nature. In the course of his analysis, he realized that the sequence was related to measurable physical and chemical

characteristics. He further found that there are two sequences of minerals, the discontinuous reaction series and the continuous reaction series.

Look at the diagram of Bowen's Reaction Series on the next page.

The Discontinuous Reaction Series

The left-hand side of Bowen's Reaction series. These are a group of mafic or iron-magnesium bearing minerals - olivine, pyroxene, amphibole, and biotite. If the chemistry of the melt is correct, these minerals react discontinuously to form the next mineral in the series. 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. As you go down Bowen's Reaction Series, the minerals increase in the proportions of silica in their composition. 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. At the crystallization temperature of amphibole, all the pyroxene will react with the melt to form amphibole and amphibole will crystallize. At the crystallization temperature of biotite, all of the amphibole will react to form biotite and biotite will crystallize. Thus all igneous rocks should only have biotite. But we know that it is not true. If you are crystallizing olivine and there is not enough silica to form pyroxene, then the reaction will not occur and olivine will remain. If you are crystallizing olivine and the temperature drops too fast for the reaction to take place (the magma is belched 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.

The Continuous Reaction Series

The right-hand side of Bowen's Reaction Series. They are the plagioclases. Plagioclase minerals have the formula $(Ca, Na)(Al, Si)_3O_8$. The highest temperature plagioclase has only calcium (Ca). The lowest temperature plagioclase has only sodium (Na). 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 to form 99% Ca and 1% Na plagioclase and 99% Ca and 1% Na plagioclase would crystallize. Then those would react to form 98% Ca and 2% Na and the same composition would crystallize. Etc. All of this is happening 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.

Examples of the use of Bowen's Reaction Series are (figure 1):

- 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 mineral associations and exclusions in a rock. The minerals in each rock are horizontal across the diagram. Basalt would have olivine, pyroxene and high calcium plagioclase, but would not have quartz and potassium feldspar.

3) The top diagram shows mineral stabilities in a weathering environment, the least stable at 1 bar and 25° C (the earth's surface). The least stable minerals are at the top of the diagram and the most stable at the bottom. A 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 will readily break down, but the quartz is fairly resistant. When the products of the weathering of basalt and granite are eroded and deposited, you would expect to find lots of quartz, maybe some potassium feldspar and muscovite, and no olivine and calcium plagioclase.

4) The rocks 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 Yellowstone National Park the two rock types are interlayered. They must have come from two different magmas.

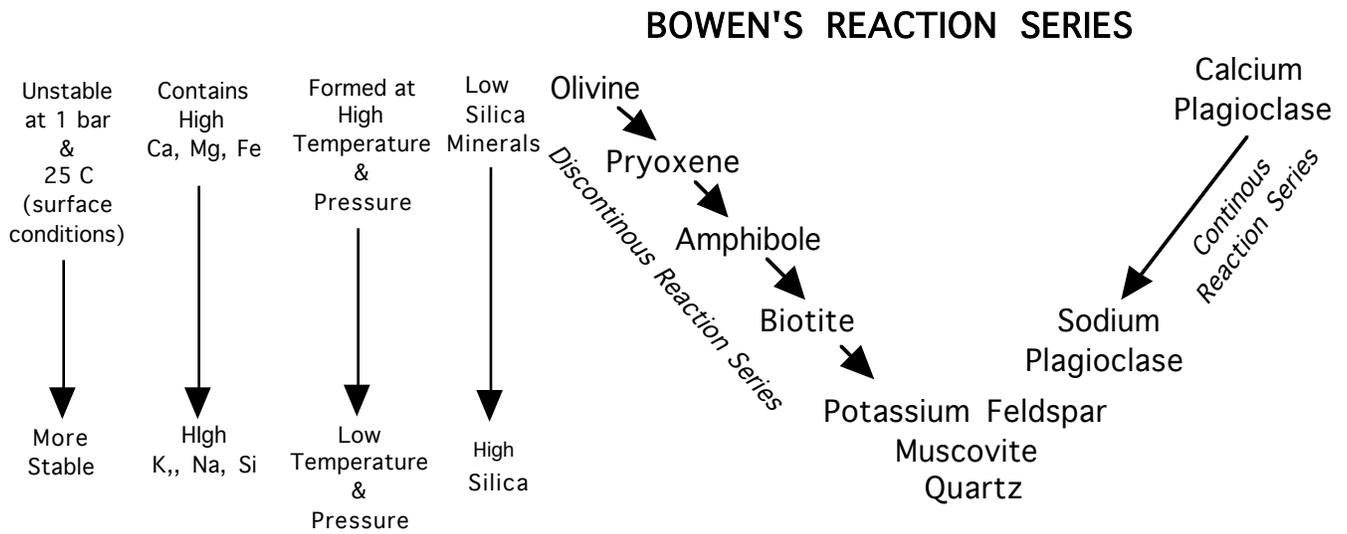
5) If a basalt has quartz in it, which occasionally occurs, the quartz must have come not from the magma, but from the rock into which the basalt was intruded.

6) The green and black beaches of the big island of Hawaii are made of olivine and pyroxene. According to Bowen's Reaction Series these minerals should be unstable and should have weathered away. They are the only minerals for forming beaches so they do, but they must be geologically young. The beaches are olivine and pyroxene because the source rocks are basalts. The calcium plagioclase has weathered quickly, but the olivine and pyroxene are more resistant and have not yet had time to weather.

7) If a basalt magma cools slowly and quietly the first minerals to form should be olivine and calcium plagioclase. These are solids in a liquid. A solid is denser than a liquid, so the olivine and plagioclase should sink to the bottom of the magma chamber. Olivine has a higher specific gravity than plagioclase. Therefore, if a thick, quiet basalt intrusion occurs it should have a layer of olivine at the bottom. The Palisades Sill on the west bank of the Hudson River in New York and New Jersey is such a body and it has a layer of pure olivine at the base. If you get a chance go see it.

8) Let's go you step further. This time take a very large (1,000 km³) and very deep (20 km.) basalt intrusion. This 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. As the temperature drops you will still have a layer of olivine and calcium plagioclase at the bottom of the magma chamber. When the temperature of the melt reaches the right you 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. Notice that you are removing Fe, Mg, and Ca from the melt. The magma must be relatively enriched in Na, K, and Si. The magma started crystallizing a gabbro. Now it will start to crystallize a diorite. The magma keeps crystallizing, so the next layers are amphibole and Na-Ca plagioclase. The magma is becoming granitic. Next to crystallize will be biotite and Na plagioclase. The remaining magma (probably as much as 10 km³) is high in Na, K and Si and will crystallize as a granite. Thus, just by the crystallizing order shown by Bowen's Reaction Series and the effects of gravity, a granitic magma is made from a basaltic you. This relationship can be seen in the Stillwater Complex in Montana.

Physical Conditions and Bowen's Reaction Series



Igneous Rocks and Bowen's Reaction Series

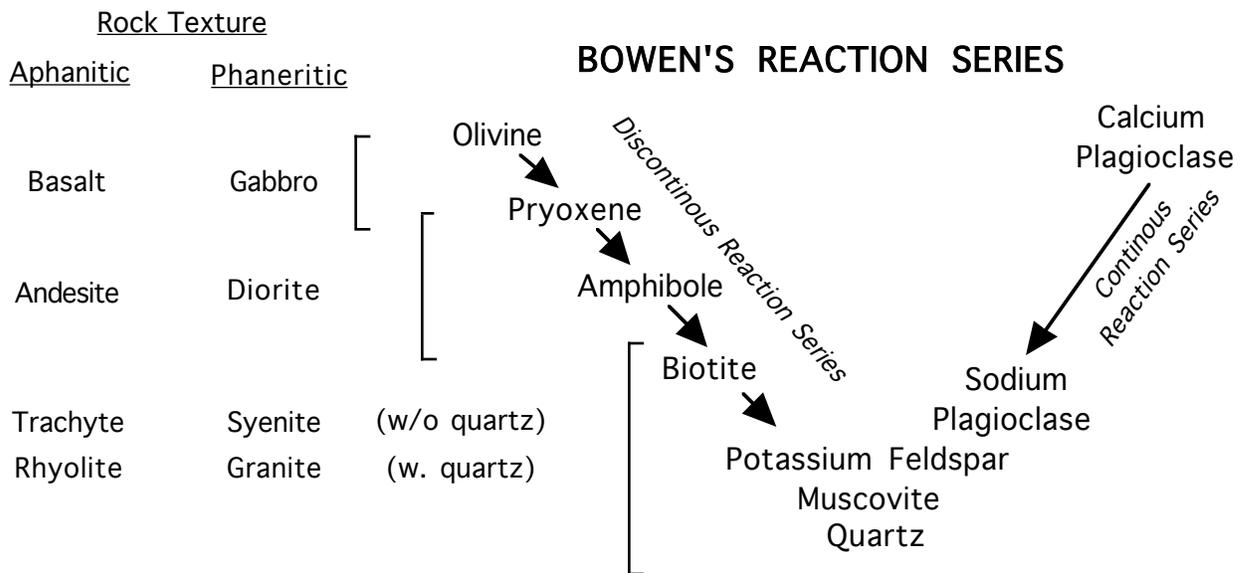


Figure 1. Bowen's Reaction Series

WORKSHEET

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

Basalt

Diorite

Granite

Gabbro

2) You have a magma that is at very high temperature and pressure.

What minerals would the rock formed from this magma have if it was intruded into the earth?

What minerals would it have if it was extruded onto the surface of the earth?

What would be the difference in these rocks?

3) Which minerals would you expect to find on a beach?

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

5) You discover that your basalt has quartz in it. Where did the quartz come from?

6) You analyze the minerals in a rock and find that it contains only olivine. How could this happen?

7) Bonus Question!!!

You stop along the side of the highway to look at a 1,000 m. high outcrop. You decide to climb to the outcrop and look at the rocks. The base of the outcrop has a layer of olivine and calcium plagioclase. 100 meters up the cliff the rock is pyroxene and a sodium-bearing calcium plagioclase. At 350 meters, the rock contains amphibole and a calcium-bearing sodic plagioclase. At 650 meters, the minerals are biotite and sodium plagioclase. From 900 meters to the top the rock is granite. Explain how this out crop could have been formed.

ANSWER SHEET

WORKSHEET

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

Basalt **olivine, pyroxene, calcium plagioclase**

Diorite **pyroxene, amphibole, sodium-bearing calcium plagioclase**

Granite **quartz, potassium plagioclase, muscovite, biotite**

Gabbro **olivine, pyroxene, calcium plagioclase**

2) You have a magma that is at very high temperature and pressure.

What minerals would the rock formed from this magma have if it was intruded into the earth?

olivine, pyroxene, calcium plagioclase

What minerals would it have if it was extruded onto the surface of the earth?

olivine, pyroxene, calcium plagioclase

What would be the difference in these rocks?

The first is phaneritic, the second aphanitic because of cooling rates. The first cooled slowly, the second fast.

3) Which minerals would you expect to find on a beach?

quartz, maybe potassium feldspar and muscovite

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

They are at the opposite ends of Bowen's Reaction Series

5) You discover that your basalt has quartz in it. Where did the quartz come from?

It had to come from the rock surrounding the magma chamber.

6) You analyze the minerals in a rock and find that it contains only olivine. How could this happen?

There were no chemicals to form the feldspars (calcium), and the rock cooled too slowly for the discontinuous reactions to take place or there was not enough silica for the reactions to take place.

7) Bonus Question!!!

You stop along the side of the highway to look at a 1,000 m. high outcrop. You decide to climb to the outcrop and look at the rocks. The base of the outcrop has a layer of olivine and calcium plagioclase. 100 meters up the cliff the rock is pyroxene and a sodium-bearing calcium plagioclase. At 350 meters, the rock contains amphibole and a calcium-bearing sodic plagioclase. At 650 meters, the minerals are biotite and sodium plagioclase. From 900 meters to the top the rock is granite. Explain how this out crop could have been formed. **See the description, Teacher Information Example #8.**