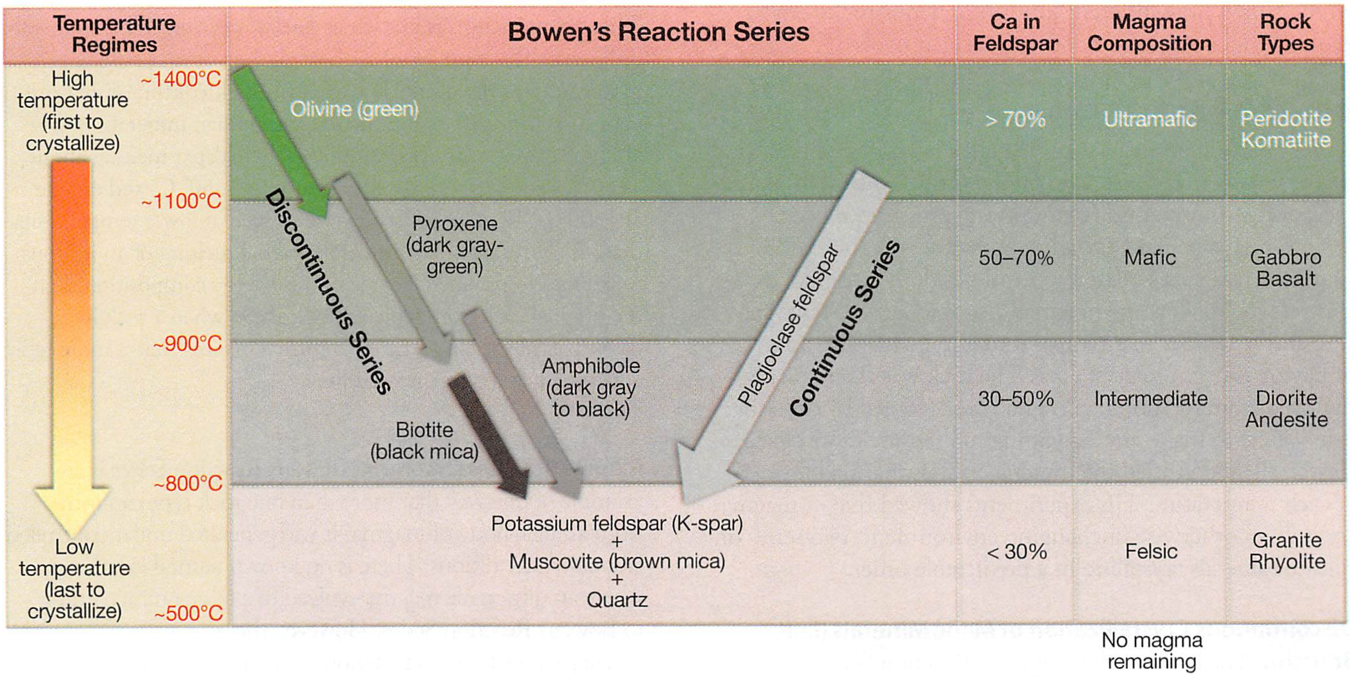

FIGURE 5.6 Bowen's Reaction Series—A laboratory-based conceptual model of one way that different kinds of igneous rocks can differentiate from a single, homogeneous body of magma as it cools. See text for discussion.

Bowen's Reaction Series

When magma intrudes Earth's crust, it cools into a mass of mineral crystals and/or glass. Yet when geologists observe and analyze the igneous rocks in a single dike, sill, or batholith, they often find that it contains more than just one kind of igneous rock. Apparently, more than one kind of igneous rock can form from a single homogeneous body of magma as it cools. American geologist, Norman L. Bowen made such observations in the early 1900s. He then devised and carried out laboratory experiments to study how magmas might evolve in ways that could explain how more than one kind of igneous rock could form from a single body of magma. His work is commonly summarized in a diagram (**FIGURE 5.6**) called **Bowen's Reaction Series**, which shows how different kinds of igneous rocks can evolve from a single body of magma as it cools.

Bowen's Experiment

Other geologic investigations had already suggested that the top of Earth's mantle is made of peridotite. So Bowen placed pieces of peridotite into *bombs*, strong pressurized ovens used to melt the rocks at high temperatures (1200–1400°C). Once the rocks had melted to form peridotite magma, Bowen would allow the magma to cool to a given temperature and remain at that temperature for a while in hopes of having it begin to crystallize. The rock was then quickly removed from the bomb and quenched (cooled by dunking it in water) to make any remaining molten rock form glass. Bowen then identified the mineral crystals that had formed at each temperature. His experiments showed that as magma cools in an otherwise unchanging environment, two series of silicate minerals crystallize in a predictable order.

Discontinuous Crystallization of Mafic Minerals (Left Branch). The left branch of Bowen's Reaction Series (**FIGURE 5.6**) shows the predictable series of mafic minerals that crystallize from a peridotite magma that is allowed to cool slowly. This series is discontinuous because one mafic mineral replaces another as the magma cools. For example, olivine is first to crystallize at very high temperature. But if the magma cools to about 1100° C, then the olivine starts to react with it and dissolve as pyroxene (next mineral in the series) starts to crystallize. More cooling of the magma causes pyroxene to react with the magma as amphibole (next mineral in the series) starts to crystallize, and so on. If the magma cools too quickly, then rock can form while one reaction is in progress and before any remaining reactions even have time to start.

Continuous Crystallization of Plagioclase (Right Branch). The right branch of Bowen's Reaction Series (**FIGURE 5.6**) shows that plagioclase feldspar crystallizes continuously from high to low temperatures (~1100–800° C), but this is accompanied by a series of continuous change in the composition of the plagioclase. The high temperature plagioclase is calcium rich and sodium poor, and the low temperature plagioclase is sodium rich and calcium poor. If the magma cools too quickly for the plagioclase to react with the magma, then a single plagioclase crystal can have a more calcium rich center and a more sodium rich rim.

Crystallization of Quartz (Bottom of the Series). Finally, notice what happens at the bottom of Bowen's Reaction Series (**FIGURE 5.6**). At the lowest temperatures, where the last crystallization of magma occurs, the remaining elements form abundant potassium feldspar (K-spar), muscovite, and quartz.

Partial Melting and Bowen's Reaction Series. When a plastic tray of ice cubes is heated in an oven, the ice cubes melt long before the plastic tray melts (i.e., the ice cubes melt at a much lower temperature). As rocks are heated, their different mineral crystals also melt at different temperatures. Therefore, at a given temperature, it is possible to have rocks that are partly molten and partly solid. This phenomenon is known as *partial melting*. When minerals of Bowen's Reaction Series are heated, they melt at different temperatures. The plagioclase feldspars melt continuously from about 1100–1500° C, but the ferromagnesian minerals, quartz, and K-feldspar melt discontinuously. K-feldspar melts at about 1250° C, pyroxene at 1400° C, quartz at 1650° C, and olivine at 1800° C. Because feldspars tend to melt at lower temperatures than the ferromagnesian minerals, partial melting of an igneous rock tends to produce magma of more felsic composition than the original rock from which it melted. So when a rock like basalt partially melts, it tends to form a magma that is more felsic and would cool to form andesite.

Magmatic Differentiation. Bowen's Reaction Series is an example of one way that more than one rock type can form from a single body of magma. It was generated under controlled laboratory conditions. There is no known natural location where an ultramafic magma evolved to a felsic one according to Bowen's Reaction Series. However, there are many examples where parts of Bowen's Reaction Series have occurred in nature.

Bowen's continuous series of crystallization leads to the depletion of calcium and sodium from the magma, so the composition of the magma changes. However, along the discontinuous series, early-formed mafic mineral crystals in a cooling body of magma have been shown to react with the magma at lower temperatures to form new mafic minerals. If this recycling of elements occurred perfectly, then the concentrations of iron and magnesium in the magma would never change. In nature, some of the early-formed crystals either settle out of the magma or are encrusted with different minerals before they can react, so they can no longer react with the original magma. This is called *fractional crystallization*. On the other hand, a magma may melt some of the wall rocks surrounding it and assimilate its elements. This is called *assimilation*. *Magma mixing* may also occur. Bowen's continuous series of crystallization, fractional crystallization, assimilation, and magma mixing are all factors that can contribute to **magmatic differentiation** (any process that causes magma composition to change). Magmatic differentiation produces more than one rock type from a single body of magma.