MAGMATIC PROCESSES LEADING TO COMPOSITIONAL DIVERSITY IN IGNEOUS ROCKS: BOWEN (1928) REVISITED

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ABSTRACT. Here we present a perspective on the evolution of thought on the origin of compositional diversity in igneous rocks, starting with the pioneer Norman Levi Bowen. In pursing this question of diversity, which was first clearly identified by Daly (1914), Bowen established the utility of experimentally determined phase equilibria as an aid to understanding geologic processes. His work ultimately led him to attribute igneous rock diversity to a singular path of fractional crystallization. We summarize the evolution of understanding acquired by petrologists during and after Bowen’s time. Experimentalists beyond Bowen were crucial in furthering the understanding of the origin of the diversity of igneous rocks by discovering that more than one fractional crystallization path can occur in nature: at a minimum, differentiation can either be dry (tholeiitic) or hydrous (calc-alkaline). We also reassess the five alternative igneous processes that may give rise to compositional diversity that Bowen considered, but found to be wanting. These are magma mixing, liquid immiscibility, Soret diffusion, compositional gradients in liquids, and contamination of magma by foreign material (assimilation). These processes play important roles in igneous petrogenesis, that is, roles larger than Bowen envisioned, yet fractional crystallization remains fundamentally important.

Keywords: fractional crystallization, magma mixing, crustal assimilation, liquid immiscibility, Soret diffusion, experimental petrology, phase equilibrium

INTRODUCTION

Norman Levi Bowen was the pioneer in establishing the field of experimental igneous petrology and by doing so illustrated the value of laboratory investigations of silicate melt - crystal systems for understanding magmatic processes. In the preface of his opus “The Evolution of the Igneous Rocks” (Bowen, 1928) he states: “While rocks themselves remain the best aid to the discussion of their origin by fractional crystallization, much light is thrown upon the problem by laboratory investigations of silicate melts.” Bowen was convinced that fractional crystallization was the most important process that led to the compositional diversity exhibited by igneous rocks. Fractional crystallization had initially gained traction after Charles Darwin flushed out the hypothesis in his 1844 book “Geological Observations on the Volcanic Islands,” but it was still considered a subordinate igneous process (Daly, 1914). Bowen strongly disagreed, further stating in his preface: “On the question of the relative importance of fractional crystallization as compared with other processes . . . I can lay no claim to an open mind . . . But upon the relative importance of the various factors that may induce fractional crystallization there is much room for an open mind.” In chapter 1 “The Problem of the Diversity of Igneous Rocks” Bowen offers up and systematically rejects, perhaps with unintended prescience, other “rival processes” that had been proposed along with fractional crystallization: magma mixing, liquid immiscibility, Soret diffusion, compositional gradients in liquids, and contamination of magma by foreign material (assimilation).

In this review we will discuss what has been learned “from the rocks themselves” and “from the various factors that induce fractional crystallization” that derived from Bowen’s ground breaking experimental studies. We will also discuss the evolution of
knowledge on the five aforementioned rival processes that Bowen brought up in chapter 1. We will survey the evolution of the discovery of new types of compositional diversity and of the advances in experimental studies since publication of Bowen’s work. It is curious to wonder if Bowen had had the opportunity to study the full complement of igneous rocks known today, might he have reconsidered his perspective that those rival processes were unimportant and secondary to fractional crystallization?

Bowen and the Evolution of Experimental Igneous Petrology

Bowen and his colleagues started experimental petrology from scratch only aided by an absolute temperature scale, the so-called Geophysical Lab Temperature scale, which his immediate predecessors (Day and Allen, 1904) had established. Bowen used this temperature scale to construct the first petrologic phase diagrams. His first experimental studies that established the phase equilibria of common rock forming minerals were performed at atmospheric pressure, in air, using Pt-wound resistance furnaces. Samples were placed in containers (usually a Pt tube), which were then suspended on thin wires and heated to high temperatures. Quenching was achieved by melting the wire using an electric current, which caused the sample to drop into a dish of water placed under the open furnace tube (this quenching technique is still widely used today). Exploring phase space required, for each experimental temperature of interest, the preparation of many starting materials that were loaded into separate Pt capsules and then simultaneously hung together. Experimental run products were examined and identified with an optical microscope after placing crushed samples on glass slides in oils with known refractive indexes, which allowed them to establish for each bulk composition whether it was above its liquidus, in a crystal + liquid field, or below the solidus.

The first compositional space Bowen studied for his Ph. D. thesis was the binary system Nepheline – Anorthite (Bowen, 1912, M.I.T.). He then studied the binary solid solution Albite – Anorthite (Bowen, 1913), the system MgO – SiO₂ in which he established the revolutionary peritectic melting behavior of Enstatite to Forsterite + Liquid (Bowen and Andersen, 1914), and the ternary system Forsterite – Diopside – SiO₂ (Bowen, 1914). In 1915, his colleague Olaf Andersen published the ternary system Forsterite – Anorthite – Silica (Andersen, 1915) and Bowen published the phase diagram for Diopside – Albite – Anorthite (Bowen, 1916). Bowen was able to apply these carefully established experimental melting relations to observed natural igneous rock mineral associations and compositions to forge the concepts that appeared in his 1928 book “The Evolution of the Igneous Rocks”. It seems a miraculous accomplishment for one person to take the information in this handful of simple system phase diagrams and create a fully developed theory for the workings of magmatic processes.

Bowen developed a whole new laboratory-based sub discipline of the Earth Sciences. Experimental petrology continues to evolve, but our debt to Bowen is enormous. As new tools and techniques became available, the field of experimental petrology moved on from simple systems to the study of chemically complex natural systems. A major step forward was the application of the electron probe micro-analyzer (EPMA) to chemical characterizations of experimental run products (Green and Ringwood, 1967; Kushiro, 1972). For the first time, crystals and coexisting melt compositions could be characterized in the experimental charge and a complete phase diagram could be built using only a single starting composition. Another breakthrough was the development of techniques for buffering oxygen fugacity in experiments at one atmosphere and at higher pressures (Nafziger and others, 1971; Sato, 1971; Huebner, 1971). A further advance was to include iron in 1-atmosphere experiments. This challenge was first solved by several groups (for example, Walker and others, 1977) during experimental investigations of the returned Apollo lunar samples. They
prevented iron loss by using metallic iron capsules held in evacuated silica glass tubes. This new approach allowed accurate measurements of FeO in melts and minerals under the extremely reducing conditions of lunar mare differentiation. Soon after Apollo, techniques for suspending droplets of natural magmas on FePt alloys were developed (Walker and others, 1979) and the calibration of the solution properties of these alloys allowed investigations of natural silicate systems to be undertaken over a wide range of oxygen fugacities (Grove, 1981).

The influence of dissolved volatiles was another important variable that Bowen explored late in his career in his study of the origin of granites (Tuttle and Bowen, 1958). Technology developed by Tuttle (1948) allowed exploration of the effects of dissolved magmatic H2O on phase relations up to 0.4 GPa and temperatures up to 800 °C. The groundbreaking work by Tuttle and Bowen (1958) on the melting of the simplified granite system (Quartz – Albite – K-Feldspar) in the presence of water demonstrated the importance of this volatile component on phase relations. Experiments with dissolved H2O within the higher temperature range relevant for crystallization of basalt magma became possible through the development of the internally heated pressure vessels (Yoder, 1950; 1952) which were applied to measuring the solubility of H2O in iron-free silicate melts (Burnham and Jahns, 1962). The first experiments on the solubility of H2O in iron-bearing basalt melts were made by Hamilton and others (1964). The next step of controlling oxygen fugacity in iron-bearing and H2O-bearing experiments was first done by Holloway and Burnham (1972), who used a Shaw membrane (Shaw, 1967) (also, they were able to report both mineral and melt compositions analyzed by EPMA). Williams (1966, 1968) developed an externally heated cold seal pressure vessel (the TZM) that can be used at temperatures up to 1200 °C and pressures up to 300 MPa. The TZM began to be used for H2O-bearing experiments at controlled oxygen fugacity in iron bearing melts (Dixon and Rutherford, 1979). Through these experimental developments it became possible to examine the influence of oxygen fugacity, dissolved magmatic volatiles, and pressure on the crystallization of natural magmas.

Since Bowen’s time, high pressure (> 300 MPa) experimental techniques have significantly expanded our understanding of the mineralogy of the Earth’s mantle and the diversity of magmas produced by mantle melting. Either developed or applied to Earth Science problems after Bowen’s career ended, these methods include the piston-cylinder (Boyd and England, 1960), the diamond anvil cell (DAC, Merrill and Bassett, 1974), and the multi-anvil device (Kawai and Endo, 1970). DAC and multi-anvil devices derived from the simple-squeezer – opposed anvil devices developed by Percy W. Bridgman (Bridgman, 1952) and eventually their development allowed for the attainment of the high temperatures and ultra-high pressures necessary for simulating lower mantle conditions. Shallower pressures could be achieved using the piston cylinder and multi-anvil devices, which were used to investigate the significant effects of pressure (Green and Ringwood, 1967; O’Neill, 1981; Takahashi, 1986; Walter, 1998) and variable H2O content (Gaetani and Grove, 1998) on the compositions of mantle melts, and the depth of critical phase transitions in the Earth’s upper mantle. Ringwood and Major (1970) determined the stability relations of majorite and ringwoodite and associated the appearance of these minerals with the 410 and 520 km seismic discontinuities. At pressures then too great to conduct experiments, Ringwood (1962) hypothesized the upper – lower mantle transition zone seismic discontinuity at 670 km was caused by a phase transition from a dominantly ringwoodite mantle assemblage to one containing bridgmanite (Ringwood called it MgSiO3 perovskite) and ferropericlase. Continued evolution of the opposed anvil and DAC methods allowed Ringwood’s hypothesis to be directly tested as obtainable experimental pressures increased making the reproduction of the mineralogy throughout the Earth’s mantle
possible. Liu (1974, 1975) first confirmed bridgmanite and ferropericlase as the stable assemblage below the 670 km discontinuity. Improvements in DAC technology have more recently led to the synthesis of a post-perovskite phase (Murikami and others, 2004; Oganov and Ono, 2004) that may be a phase transition linked to the D” discontinuity at the base of the lower mantle (2900 km) right above the core – mantle boundary.

“While Rocks Themselves Remain the Best Aid . . .”

Bowen was limited in 1928 at the time of writing “The Evolution of the Igneous Rocks” by the amount of information available on the compositional variability exhibited by igneous rocks, which only included major element data (and no trace element or isotopic data). At the time of publication of Bowen’s book, Henry S. Washington had compiled basalts from the British Tertiary Province, the Deccan Traps in India, and various Pacific ocean islands and had published average compositions in his paper “The average chemical composition of igneous rocks” (Clark and Washington, 1922). Most of the 5519 analyses were silica–rich samples. By contrast, today, the PetDB database contains 1,174,126 bulk rock analyses and 655,267 analyses of volcanic glasses as of October 1, 2016 and includes a range of iron – rich to silica – rich samples. Also during Bowen’s time, the Skaergaard intrusion in east Greenland had not yet been discovered (Wager and Deer, 1939) and basalts from mid-ocean ridges had not yet been dredged from the ocean floor (Muir and others, 1964) although Bowen understood that the oceanic crust was likely more mafic than the continental crust. Plate tectonic theory had not been conceived, and would not be until the 1960’s.

Given that there were only a small number of rocks that had been analyzed at the time, Bowen focused on 335 subalkaline basalts for which compositions had been determined and that he thought of as potential parental magmas. In the end, Bowen’s skepticism of using rocks that might not represent liquids caused him to base his discussion of the liquid line of descent followed during fractional crystallization of natural magmas to rock associations from subduction zones (such as Lassen, California and Katmai, Alaska) because they were, at the time, the only rocks that clearly preserved liquid compositions (Bowen’s glassy rocks). He also extensively discussed the liquid versus cumulate compositional relationship between the lavas and intrusive rocks, respectively, of the British Tertiary province. Ironically, this particular rock series subsequently was shown to represent a different differentiation trend (a tholeiitic trend) than the one Bowen discussed (a calc-alkaline trend) due to processes he largely dismissed: modification by crustal assimilation and magma mixing (Sparks, 1988; Kerr and others, 1999).

A critical assumption made by Daly (1914) and Bowen (1928) was the existence of a single primary magma whose composition was effectively the same everywhere (that is, basaltic, not granitic). This view persisted into the mid 1960’s (Engel and others, 1965). It was not until high pressure - high temperature experimental studies on primary basalts of variable composition revealed the existence of a low pressure thermal divide which separated silica under-saturated (alkali) basalts from sub-alkaline and tholeiitic basalts (Yoder and Tilley, 1962). The thermal divide causes liquids on either side of the divide to follow distinct down temperature crystal fractionation paths that produce different residual liquid compositions. This discovery conflicts with Bowen’s hypothesis that both silica-saturated and silica under-saturated magma could be produced by means of fractional crystallization from essentially the same basaltic parent, although he acknowledged in his preface that this conclusion should be “regarded as resting on a less certain foundation” because it lacked direct experimental evidence. He reasoned that silica under-saturated residual liquids could be produced under certain circumstances, either by minimal early olivine-fractionation, some later pyroxene fractionation, and the incongruent melting of orthoclase, or by
quartz fractionation in the presence of water. Bowen’s rationale here exemplifies his thinking that the only “flexibility in the course of crystallization” he would entertain was in the extent of efficient fractionation (that is, non-fractional crystallization could occur), which he did not consider to be a true alternate liquid line of descent.

In 1967, Green and Ringwood addressed the question as to the origin of the primary liquids on either side of the thermal divide by using high-pressure experimental petrology, and thereby demonstrated the existence of a range of primary, mantle-derived melts whose compositions changed as a function of mantle melting depth. They found that at greater depths in the mantle, silica-undersaturated alkali-olivine basalts were generated, while at shallower depths olivine tholeiites and silica-saturated tholeiites were produced. Therefore, there could be many different mantle-derived primary magmas of differing chemical composition that might be expected to undergo different fractional crystallization processes. Thus, this established that silica-undersaturated basalts follow a distinct alkalic differentiation series on the nepheline-normative side of the thermal divide that was not recognized in Bowen’s time. In other instances the wide range of compositional variability in mid-ocean ridge primary basalts records mantle melting over a range of temperatures and depths (Klein and Langmuir, 1987; Kinzler and Grove, 1992), yet these diverse primary magmas follow the same low-pressure tholeiitic differentiation trends.

It is prudent for us to keep in mind that the debate on the nature of primary magmas during Bowen’s time centered on if they were mafic/basaltic or felsic/granitic in composition rather than if basaltic primary melts could have significantly variable compositions. In truth, there was not enough data for petrologists at the time to rigorously consider this variable, and Bowen himself defined a basaltic magma as any magma that “on rapid crystallization, gives rise to a rock having intermediate plagioclase and clinopyroxene as its principle constituents”. So while Bowen was correct in thinking that most igneous rocks are indeed ultimately derived from basaltic primary melts, his assumption that primary basalts are globally uniform and that variations in primary basalt composition would not lead to appreciable differences in the course of fractional crystallization was clearly an oversimplification. In 1928 the theory of plate tectonics was decades away, and so Bowen would not have had much appreciation for the fact that mantle melting occurs by different processes in different locations (that is, Bowen thought that adiabatic decompression melting was the only important mantle melting process). Accordingly, he would also not have realized that his strict criteria for trustworthy data, of which there was not much of to begin with, might inadvertently lead him to overlook critical igneous variations by only focusing on variations at subduction zone or plateau basalts settings. Importantly, subduction zone primary magmas are distinct from other primary magmas in that they contain significant amounts of dissolved H₂O (Sisson and Grove, 1993; Gaetani and Grove, 1998), and their major element compositions can range from olivine tholeiite to quartz tholeiite. It is differentiation of these H₂O-bearing basaltic magmas at crustal levels that leads to the development of the calc-alkaline trend. While Bowen and others appreciated the role of H₂O on phase equilibria in rocks with hydrous minerals [that is, typically more felsic rocks, for example, Tuttle and Bowen (1958)], this perspective did not extend to basalts and it was not until Sisson and Grove (1993) discovered that mafic magmas could be hydrous without crystalizing hydrous minerals that an appreciation for hydrous basaltic parental magmas and their effect on differentiation trends was established (Carmichael, 2002).

**FRACTIONAL CRYSTALLIZATION OF BASALT UNDER ANHYDROUS (DRY) CONDITIONS: THE THOLEIITIC TREND**

The analyzed lava suites from Lassen, California and Katmai, Alaska showed a trend of iron-depletion and silica-enrichment that Bowen interpreted as the liquid line
of descent followed by a crystallizing basaltic melt. His colleague, Clarence Norman Fenner, disagreed, arguing that the normal course of fractional crystallization should be one of iron-enrichment (Fenner, 1926, 1931, 1948). Fenner based his reasoning on plutonic rocks by separately analyzing the chemical compositions of the bulk rock and the pyroxene contained within. Fenner found that the pyroxene always had a higher Mg/Fe than the whole rock and concluded that a differentiation trend that resulted from crystallization of plagioclase + pyroxene should show iron-enrichment. Further support for iron-enrichment during fractional crystallization came from analysis of layered rocks from the Skaergaard intrusion by Wager and Deer (1939). Wager and Deer concluded “the trend of fractional crystallization of the Skaergaard magma during the early and middle stages supports Fenner’s view that during fractional crystallization of basalts there is absolute enrichment in iron.” Wager and Deer (1939) also pointed out that after 95 percent solidification and extreme fractionation, the silica contents of the residual magmas did not “rise beyond the limits of normal basic rocks.” They went on to state “the normal calc-alkaline series of igneous rocks is frequently considered to represent the result of crystal fractionation of basalt magma. From the evidence of the Skaergaard it appears that crystal fractionation of basalt leads to ferrogabbro and not to intermediate rocks of the calc-alkaline series.” Both Fenner and Wager and Deer favored mixing of basalt and silicic magma to explain the calc-alkaline series, which we will discuss in the Magma Mixing and Assimilation section found below.

Suites of igneous rocks that exhibit iron-enrichment at constant SiO₂ became known as the tholeiitic series (Daly, 1952). Because Bowen only relied on liquids for evidence, he was not convinced of the iron-enrichment differentiation trend found in the plutonic Skaergaard environment. The first true liquids measured that preserved iron-enrichment trends were basaltic lavas from Iceland (Carmichael, 1964) and the Galapagos (McBirney and Williams, 1969), years after Bowen’s passing in 1956. Kuno (1965) analyzed the products of in-situ differentiation within single lavas flows (that is, segregation veins containing from 14 to 18 wt. % FeO) that followed the iron-enrichment trend in lava flows from Hawaii, Japan and California. The most spectacularly preserved tholeiitic liquid line of descent is associated with the Galapagos Spreading Center (Byerly, 1980; Perfit and Fornari, 1983; Fornari and others, 1983; Juster and others, 1989). Submarine pillow lavas erupted from the Galapagos Spreading Center are mantled by glassy chill margins that would have immediately gotten the attention of Bowen. The maximum FeO content within this glass suite is 18 weight percent FeO at 3.7 percent MgO (fig. 1). Galapagos Spreading Center magmas range from basalt, to Fe-Ti rich basalt, andesite and rhyodacite.

Juster and others (1989) performed one-atmosphere experiments on a Galapagos parental composition over a range of oxygen fugacities from QFM (quartz-fayalite-magnetite buffer) to NNO + 2 (two log units above the Nickel – Nickel oxide buffer). The liquidus of the starting composition is saturated with olivine (oliv) and plagioclase (plag). After a small amount of oliv + plag crystallization, augite joins the crystallizing assemblage (fig. 2). Olivine, plagioclase and augite co-precipitate over a short temperature interval before pigeonite joins the crystallizing assemblage at a peritectic reaction boundary. At this reaction boundary olivine + melt react to form plagioclase + augite + pigeonite. Olivine disappears, a Fe-Ti rich spinel phase saturates and crystallization continues with the assemblage plag + augite + pigeonite + spinel.

The resulting saturation boundaries inferred from these experiments along with analyses of the glassy chill margins of Galapagos Spreading Center lavas from 85 °W are shown in figure 1. As is evident in the variation diagrams, crystallization leads to strong enrichment in FeO at nearly constant SiO₂ and decreasing Al₂O₃ that is the result of early and modally abundant crystallization of plagioclase (Grove and Baker, 1984). At
Fig. 1. (A) Saturation boundaries determined in experiments on a Galapagos lava (Juster and others, 1989) are plotted along with glass compositions measured in mid-ocean ridge basalts from 15 segments along the Galapagos Spreading Center (Gale and others, 2013) in the pseudo-ternary projections Olivine – Augite – Quartz and Olivine Plagioclase – Quartz using oxygen units (see Tormey and others, 1987). (B) Experimentally determined liquid lines of descent from Juster and others (1989) are plotted with glass analyses from the same 15 segments along the Galapagos Spreading Center as in figure 1A (Gale and others, 2013) on MgO vs. SiO₂, MgO vs. Al₂O₃, MgO vs. TiO₂ and MgO vs. FeO variation diagrams.
low-pressure and under anhydrous conditions plagioclase dominates the crystallization assemblage (oliv: plag = 30:70 by weight). Once augite joins as a crystallizing phase, plagioclase still dominates the precipitating assemblage (oliv: plag: augite = 16:60:24 by weight) and iron-enrichment continues until FeO has increased to 16 weight percent. Iron-enrichment continues at the reaction boundary as iron-rich olivine dissolves and silicate phases with lower-iron contents (plagioclase + augite + pigeonite) crystallize. This iron-enrichment continues until olivine reacts out and/or Fe-Ti rich spinel joins the crystallizing assemblage, at which point SiO₂ and Al₂O₃ increase with decreasing MgO, FeO and TiO₂ until the residual melt evolves to a rhyolite composition.

The compositional variability followed by mid-ocean ridge basalts (MORBs) during low pressure, anhydrous fractional crystallization as exemplified by the Galapagos Spreading Center lavas (fig. 1) is now well established as the tholeiitic or iron-enrichment trend. The first research on the compositions and petrographic characteristics of MORB did not appear until the work of Muir and others (1964). The subsequent experiments on MORB liquids showed that primitive magmas would crystallize abundant plagioclase, resulting in the inferred iron-enrichment trend. The
pre-MORB petrologists, who discovered iron-enrichment, did so indirectly by calculating the residual liquids that were generated by in situ fractional crystallization in Skaergaard-like magma chambers. Figure 3 shows several estimates of the iron-enrichment of residual liquids inferred for the Skaergaard from Wager and Brown (1968), McBirney and Naslund (1990), Tegner (1997), Thy and others (2009), Toplis and Carroll (1995) and Hunter and Sparks (1987). Note in figure 3 that all of these estimates of iron-enrichment cross into the experimentally determined field for silicate liquid immiscibility (Charlier and others, 2013). Also note that the tholeiitic trends all show Fe-enrichment during the bulk of crystallization. At 90 to 95 percent crystallization there is a rapid Fe-depletion and Si-enrichment trend that passes through the field of silicate liquid immiscibility. We will return to this issue in the Magma Mixing and Assimilation section found below.

Fractional Crystallization of Basalt under Hydrous (Wet) Conditions: The Calc-Alkaline Trend

The compositional evolution of sub-alkaline lavas during fractional crystallization considered by Bowen to be the true and only path of liquid evolution is now referred to as the calc-alkaline trend. It is characterized by depletion in FeO with increasing SiO₂. Yet, inescapable field evidence from the Skaergaard led petrologists to increasingly recognize that many, if not most, basalts followed a tholeiitic, Fe-enrichment path during fractional crystallization, and so they looked for alternative ways to produce the calc-alkaline trend. In a review Kennedy (1955) suggested that water dissolved in the melt might be important in promoting calc-alkaline differentiation and thereby apparently resolved the Bowen – Fenner controversy. Kennedy thought that the addition of H₂O would cause oxidation of the magma and the early precipitation of a Fe-oxide mineral could produce the silica enrichment – iron depletion trend. Meanwhile, Osborn (1959), Presnall (1966) and Roeder and Osborn (1966) carried out experiments on dry, FeO-bearing basalt analog systems at 1-atm over a range of oxidizing conditions and found that an iron-depletion trend would only occur under

![Figure 3. SiO₂ vs. FeO variation diagram (from Charlier and others, 2013) showing liquid lines of descent that have been proposed for the Skaergaard intrusion, East Greenland. The two stars (Jakobsen and others, 2005) are compositions of immiscible melts measured in Skaergaard melt inclusions in apatite. Gray shaded region is the field of liquid immiscibility experimentally determined by Charlier and Grove (2012).](image_url)
very, very oxidizing conditions - conditions much more oxidizing than those found in the Earth’s crust. Although they produced a negative result (regarding Fe-depletion trends in oxidized, dry systems), they proved that there must be more than one type of liquid line of descent.

Sisson and Grove (1993a, 1993b) performed the first experiments that examined the effects of H\textsubscript{2}O on basalt crystallization at 100 and 200 MPa and at oxygen fugacities relevant for the crust (Nickel – Nickel oxide buffer or NNO). They found that crystallization in the presence of dissolved H\textsubscript{2}O at crustal pressures has three dramatic effects: (1) the liquidus temperature is lower, (2) the order of phase appearance changes, and (3) the compositions of the crystallizing minerals change systematically. Under one-atmosphere anhydrous conditions at the QFM buffer a primitive high-magnesian andesite (Krawczynski and others, 2012) crystallizes olivine as the liquidus phase at 1230 °C. Plagioclase joins the crystallizing assemblage at 1200 °C, followed by orthopyroxene at 1195 °C, and then augite at 1180 °C. Olivine reacts out and plagioclase + augite + /− spinel co-crystallize down to the lowest temperature investigated (1110 °C). This crystallization results in an iron-enrichment trend. Under 200 MPa H\textsubscript{2}O-saturated conditions at the NNO, olivine is the liquidus at 1160 °C, augite + /− spinel join the crystallizing assemblage at 1080 °C, and orthopyroxene (opx) appears at 1030 °C. Olivine reacts with the liquid and plagioclase appears at 990 °C. Amphibole joins the crystallizing assemblage at 910 °C. For this composition the effect
of H$_2$O is to suppress plagioclase appearance by 210 °C. The early crystallization of olivine, augite and opx and the delay in plagioclase crystallization leads to iron depletion and silica enrichment (see fig. 5 in Krawczynski and others, 2012).

The effects of H$_2$O on phase appearance, relative to the dry iron-enrichment trend, are critical to the characteristic early calc-alkaline silica-enrichment trend that develops during fractional crystallization (Sisson and Grove, 1993a, 1993b).
Plagioclase (an iron-poor mineral) stability is significantly depressed, causing it to no longer be an early crystallizing phase when modest amounts of H₂O (3–6 wt. %) are present in the melt at upper crustal pressures. Instead, olivine and augite crystallize at the liquidus and these ferromagnesian minerals deplete the melt in FeO and MgO while enriching it in SiO₂. When plagioclase appears at lower temperatures, it is in lesser proportion to the Fe-Mg silicates and it is very anorthite-rich (that is CaO-rich, SiO₂-poor and Na₂O-poor) further promoting SiO₂- and alkali-enrichment. All silicate phases are affected by the presence of water in comparison to anhydrous conditions: plagioclase appearance is lowered by over 200 °C, and olivine and augite appearance is lowered by 100 to 150 °C (fig. 4). However, the addition of H₂O does not have a similar effect on the appearance temperature of iron-rich oxide phases, that is, the appearance temperature remains the same in both anhydrous and hydrous melts. In anhydrous systems, oxides become stable 150 to 200 °C below the liquidus, which is the same temperature offset the hydrous liquidus is depressed by compared to the anhydrous liquidus, resulting in stable oxides near the liquidus. Thus silica-free, iron-bearing oxides fractionate earlier, further causing silica-enrichment and iron-depletion.

The changes in the saturation boundaries caused by the addition of H₂O are illustrated in figure 5 in pseudo-ternary mineral component projections. The plagioclase primary phase volume shrinks at high melt H₂O contents. Thus a basaltic melt that has olivine and plagioclase as near-liquidus phases under anhydrous conditions finds itself in the olivine only primary phase volume under hydrous conditions. Such melts crystallize olivine until they reach the olivine + augite saturation boundary, at which point they crystallize these two phases until multiple saturation with olivine + augite + plagioclase occurs. Liquids residual to hydrous fractional crystallization thereby become enriched in normative plagioclase and then in SiO₂.

Although Bowen did not know about the dramatic effects that H₂O could have had on phase equilibria, one can imagine that he would have been fascinated by the effects on mineral composition, phase stability, and appearance temperature. The vapor-saturated phase relations shown in figure 4 for a primitive basaltic andesite (Krawczynski and others, 2012) show that increasing dissolved water contents of the melt by increasing pressure at vapor-saturation leads to further dramatic changes in the mineral appearance temperature and mineral phase stability. Increased H₂O solubility at 500 MPa (melt H₂O of 8 wt. %) continues to destabilize plagioclase appearance (~300 °C) and increase the stability field and change the composition of amphibole. At 800 MPa (melt H₂O of 12 wt. %) the olivine liquidus temperature is depressed by ~150 °C and augite and opx appear simultaneously ~10 °C below the liquidus, followed by a high-magnesian amphibole ~60 °C below the liquidus. Krawczynski and others (2012) show that the liquid lines of descent defined by crystallization at 500 and 800 MPa, under vapor-saturated conditions, are difficult to distinguish from 200 MPa crystallization paths, primarily because the compositional effects of Mg-Fe silicate crystallization are similar (olivine – augite – opx) and thus the major element melt compositional paths are not diagnostic of crystallization pressure at vapor-saturation.

Conversely, the compositions of amphibole, olivine, opx and cpx are very sensitive to crystallization pressure. A prime example of this is the Mg# variations of opx, augite and amphibole in the first appearing minerals in vapor-saturated experiments from 200 to 800 MPa (fig. 4). Amphibole Mg# changes from 74.7 at 200 MPa to 79.9 at 500 MPa and to 83.3 at 800 MPa. Krawczynski and others (2012) used this variation in mineral composition (along with its variation with fO₂) to calibrate an amphibole Mg# geobarometer – hygrometer. When this barometer-hygrometer is applied to amphiboles preserved in mixed andesites from Mt. Shasta volcano in N. California,
they are found to have crystallized over a depth range from 276 to 948 MPa (from shallow crust to the base of the crust beneath Mt. Shasta) with the higher pressure, high-Mg# amphiboles having crystallized from melts that contained up to 14 to 15 weight percent H2O. Similar high-Mg# amphiboles occur in lavas from Mt. St. Helens, Redoubt, El Reventador and Soufriere Hills (Ridolfi and others 2010). This suggests that melting/crystallization processes in subduction zone magmas occur over a wider range of magmatic water contents.

bowen’s rival igneous processes

Magma Mixing and Assimilation

Bowen, on p. 1 of his textbook, “found [magma mixing] to fail so completely” that it could not even be considered as an important igneous processes. In the context of the time this remark is understandable, because hypotheses were in play that explained the compositional variability in igneous rocks by mixing of two primary end-member magmas: basalt and rhyolite (for example, Fenner, 1937, 1948). However, there were also some excellent discussions and descriptions of magma mixing and mingling in lavas from the Lassen region (Finch and Anderson, 1930), Hakone volcano in Japan (Kuno, 1936), and the silicic ash flow tuffs of the San Juan Mountains in Colorado (Larsen and others, 1938a, 1938b) where compositional and textural evidence convincingly showed that magmas of contrasting composition had intermixed. These authors used Bowen’s work on the appearance sequence of minerals to argue for the mixing of mafic and silicic melts. Bowen seems to have paid no attention to these works and the igneous petrology community fell silent on this topic for nearly four decades. Magma mixing was “rediscovered” in the 1970’s at subduction zone volcanoes (Anderson, 1976), in mid-ocean ridge basalts (Dungan and Rhodes, 1978), and as a trigger for explosive silicic eruptions (Sparks and others, 1977).

Bowen discussed assimilation exhaustively, and laid out the thermal energy balance that would be necessary for assimilation to occur. He pointed out that most mafic magmas are near or below their liquidus when they encounter crustal xenoliths or wallrocks in crustal magma chamber conduits, and that the heat for assimilation must come from the latent heat of crystallization in the solidifying magma bodies themselves. Given this constraint, Bowen did acknowledge that assimilation could indeed occur, for example, he ended his chapter 10 on assimilation with the conclusion: “magmas may incorporate considerable quantities of foreign inclusions” but argued that “it is doubtful whether the presence of foreign matter is ever essential to the production of any particular type of differentiate.” By this Bowen meant that the results of assimilation would be to move the magma further along the same path it would have followed anyway, because there was only one course of fractional crystallization. What petrologists discovered when examining the evidence preserved in erupted lavas was something quite different.

At Medicine Lake, a Cascade rear-arc volcano in N. California, Grove and others (1982, 1988), Baker and others (1991) and Donnelly-Nolan and others (1990) carried out field, geochemical and experimental petrology studies of an observed calc-alkaline trend preserved in a subset of the lavas erupted there. It turns out that Medicine Lake, in addition to erupting wet primitive basalts (Kinzel and others, 2000), erupted dry primitive high-alumina olivine tholeiites (HAOT), and experimental studies of these magmas under anhydrous, low-pressure conditions showed that they crystallized along iron-enrichment trends. The liquidus phases, olivine + plagioclase, crystallize until about 30 weight percent crystallization, at which point augite also begins to crystallize. Ultimately the liquid line of descent reaches a reaction boundary where olivine + liquid react to form plagioclase + augite + pigeonite, thereby continuing the trend of iron-enrichment at low SiO2 contents. However, the 3000-year-old Burnt Lava andesitic
lava flow (0.33 km$^3$) at Medicine Lake Volcano, which contains both inclusions of primitive HAOT and melted granitic crust (Grove and others, 1988; Donnelly-Nolan and others, 2016), shows a calc-alkaline trend with between 56.8 to 58 weight percent SiO$_2$ and not a tholeiitic trend. It also contains a texturally and compositionally complex assemblage of minerals including Mg-rich and Fe-rich olivine (Fo$_{88}$ and Fo$_{70}$), An-rich and An-poor plagioclase (An$_{85}$ and An$_{30}$), and Fe-rich augite (Mg$^\#_{} = 72$). Grove and others (1988) used petrologic and geochemical evidence to model the processes that led to the formation of this mixed andesite. They calculated a value of $r$ ($r = \text{mass assimilated/mass fractionated}$) of $\sim 1.35$, which requires a large amount of assimilation of granitic crust to produce the andesite of Burnt Lava. In contrast, estimates of the thermal energy budget for the shallow Burnt Lava magma reservoir predict much lower $r$ values near 0.25 (DePaolo, 1981). Therefore, the magma body itself could not supply enough heat to melt the wallrock alone, requiring an open system assimilation process in which heat and mass transfer are decoupled. Two viable realistic processes using this constraint envisioned by Grove and others (1988) for forming the Andesite of Burnt Lava are illustrated in figure 6 as either intrusive geometries of dike swarms (fig. 6A) or in a magma chamber (fig. 6B). In both cases, dry, primitive basaltic magma is emplaced at shallow crustal depths into subvolcanic granitic country rock where it undergoes fractional crystallization to an iron-rich tholeiitic magma. The Mg$^\#$ of the crystallizing iron-rich augite preserved in the mixed andesite indicates that the FeO content of the iron-rich tholeiitic magma at that point would have reached 13.2 weight percent. The latent heat released from crystallization to this iron-rich differentiated liquid (63 wt. % crystallized) heats up and melts the surrounding granitic wall rock. These two subjacent magmas (the iron-rich tholeite and the melted granitic rock) then mix to form the hybrid Burnt Lava andesite when another batch of primitive HAOT is injected into the system. Accordingly, in this type of model magma evolution is an open system characterized by $fr$actionation, $as$similation, and $mix$ing with new inputs of $re$charged primitive basalt (FARM) in which heat and mass transfer are separated in time.

Naturally, this occurs because volcanic systems are episodic and magma chambers experience repeated injections of primitive magmas. Consequently, the physical processes of recharge and mixing set the mass fraction of the three-component mixture resulting in a misleadingly large $r$ value. Models that assume a continuous process of assimilation occurring during fractional crystallization do not work: there simply is not enough heat.

Another well-preserved example of the FARM process at Medicine Lake is found in the lavas of the 10,500-year-old Giant Crater lava field (4.4 km$^3$, Donnelly-Nolan and others, 1990; Baker and others, 1991). Mapping, sampling, petrological, and geochemical analyses reveal a process similar to that inferred for the Burnt Lava case. Six erupted units preserve evidence for fractionation, assimilation, recharge, and mixing. The earliest Group 1 lavas erupted are the most evolved (53.5 % SiO$_2$ and 5.3 % MgO) and the last erupted Group 6 HAOT lavas are the most primitive (48 % SiO$_2$ and 10.5 % MgO). The most contaminated eruptive phase (Group 1) contains a texturally and compositionally complex assemblage of minerals including Mg-rich and Fe-rich olivines plus An-rich and An-poor plagioclase crystals. Partly melted granitic xenoliths and inclusions of ferrobasalt containing olivine, plagioclase and augite are also preserved. The latter phenocrysts record crystallization from an iron-rich tholeiitic liquid containing 15 weight percent FeO. The calc-alkaline compositional trend exhibited by the six eruptive units is shown schematically in figure 7, along with the tholeiitic fractionation trend that is required to produce the olivine + plagioclase + augite inclusions found in the Group 1 lavas. The open circles show a continuous assimilation and fractional
crystallization model with $r = 1.5$, and the squares are models of a FARM process that closely matches the observed compositional variations.

Major and trace element consequences of fractional crystallization can be extensively overprinted and modified in open magmatic systems. Post-mixing crystallization in hybrid magmas may move liquids along different saturation boundaries and the crystallization paths may involve different mineral assemblages than would be expected during closed-system fractional crystallization (Grove and others, 1982). Crustal assimilation and mixing cause incompatible element abundances in magmas to reach concentrations much greater than those expected from closed-system fractional crystallization alone. For example, the $> 10$-fold increase in $K_2O$ in the Giant Crater lavas (fig. 7) cannot otherwise be explained.

Fig. 6. Cartoon from Grove and others (1988) of two ways that FARM magma chamber processes could take place. (A) A series of dikes of basalt intrude, heat and melt the shallow crust as they crystallize. (B) A magma chamber where parental basalt crystallizes and heats and melts crust. In both replenishment of the magma chamber by a fresh batch of parent magma triggers magma mixing.
In summary, both Burnt Lava and Giant Crater are examples of calc-alkaline trends that exhibit silica enrichment and iron depletion but were produced by fractional crystallization along an iron-enrichment (tholeiitic) trend that has largely been erased by mixing with melted granitic crust and new pulses of primitive HAOT. The tholeiitic fractional crystallization trend is only partially preserved in the compositional variation of the last stage of magmatism at Giant Crater in the Group 6 lavas. Importantly, the distinctive calc-alkaline trend found at these field sites is not a hydrous liquid line of descent, but a multiple magmas mixing trend. Therefore, calc-alkaline trends can be produced by either hydrous fractional crystallization or by some combination of assimilation and magma
mixing. It turns out that Fenner’s mixing hypothesis, which he largely based on field relations to produce calc-alkaline trends (for example, Fenner, 1937, 1948) had some basis in reality. Bowen proposed that the compositional variability in the lavas and intrusive rocks at Mull were generated by calc-alkaline fractional crystallization, but subsequent studies (Sparks, 1988; Kerr and others, 1999) show that assimilation and multiple magmas mixing also led to the observed compositional variations. Thus, contrary to Bowen, magma mixing and assimilation do have important consequences as magmatic differentiation processes.

Compositional Gradients in Liquids

Bowen also thought it unlikely that compositional gradients “produced by the force of gravity” could exist in magma chambers or be important influences in shaping compositional evolution. However, the Bishop Tuff, a 0.7 million year old 600 km³ eruption, preserves a compositionally and thermally zoned magma chamber (Hildreth, 1979; Hildreth and Wilson, 2007). The compositional zoning formed when multiple batches of melt, released from a deep crystal-rich mush zone deeper in the magma chamber, rose each to their own level of neutral buoyancy in a density stratified magma body. Fractional crystallization was the dominant process that led to the observed compositional zonation (but see the Soret Effect section below). Further evidence for compositional gradients in magma chambers can also be found at Burnt Lava and Giant Crater (discussed in the Magma Mixing and Assimilation section). There, dense ferrobasalt was trapped beneath less dense melted granite and when a parental mafic magma with intermediate density was injected into the magma chamber, it rose through the ferrobasalt to the interface between rhyolite and basalt, triggering mixing. The physical properties of the liquids (density, viscosity) and the sequencing of intrusive processes govern the physical processes leading to compositional zoning. Huppert and Sparks (1980, 1988), Campbell and Turner (1987) and McBirney and others (1985) outline the processes that control the development of compositional stratification when basalt magma intrudes granitic crust.

Liquid Immiscibility

Bowen devoted chapter 2 of “The Evolution of the Igneous Rocks” to liquid immiscibility beginning with the statement: “In no case has any petrologist advocating this process been able to point out exactly how it is to be applied to any particular series of rocks.” Just before the publication of Bowen’s book, Greig (1927a, 1927b) showed experimentally that liquid immiscibility occurred in the high - SiO₂ portions of the two-component systems: MgO – SiO₂, CaO – SiO₂, FeO – SiO₂ and Fe₂O₃ – SiO₂, where known glassy rocks do not plot. Bowen noted that no rocks had been found that preserved the requisite emulsion of globules of contrasting compositions expected to be present in rocks if immiscibility were operating. He also realized that immiscible liquids would both crystallize a common mineral assemblage and have the same equilibrium mineral compositions. Based on this constraint, he ended his discussion by pointing out that there is no evidence that basalt and rhyolite could be related by liquid immiscibility, because these two compositions had been observed to crystallize mineral phases of extremely different composition (for example, Na-rich plagioclase in rhyolite vs. Ca-rich plagioclase in basalt). We now understand that contrasting mineral assemblages in basalt and rhyolite are produced by fractional crystallization along either the tholeiitic trend or the calc-alkaline trend, which is in agreement with Bowen’s conclusion.

Ironically, we additionally know now that liquid immiscibility does occur in natural magmatic systems but only in very FeO-rich liquids that form along the iron-enrichment (tholeiitic) differentiation trend that Bowen had dismissed. The
experimental study of Roedder (1951) on the system Fayalite – Leucite – SiO₂ led to the discovery of a large field of liquid immiscibility in the center of this ternary system. The first lunar samples from the Apollo 11 landing site were iron- and titanium-rich basalts, and these contained the abundant immiscible melt blebs in the mesostasis (Roedder and Weiblen, 1970). The immiscible melts consisted of coexisting silica-rich, iron-poor and silica-poor, iron-rich pairs and their discovery established the viability of liquid immiscibility in natural systems. More immiscible liquid blebs were discovered in the groundmasses of Deccan Traps lavas (De, 1974), in mid-ocean ridge basalts (Sato, 1978), and in a number of tholeiitic basalts (Philpotts, 1979). Dixon and Rutherford (1979) experimentally produced liquid immiscibility in tholeites and suggested that plagiogranites in ophiolites and mid-ocean ridge settings might be produced by liquid immiscibility. This idea did not gain popularity, because of the absence of a coexisting complimentary iron-rich, low-silica liquid. However, evidence for silicate liquid immiscibility has been identified in mafic layered intrusions including the Skæregård (McBirney, 1975; Jakobsen and others, 2005, 2011), Bushveld (VanTongeren and Mathez, 2012), Duluth gabbro (Ripley and others, 1998) and Sept Iles (Namur and others, 2010, 2012), where silica-rich and iron-rich melts can be observed to have segregated at the mm- to meter scale, and where melt inclusions in cumulus minerals preserve coexisting immiscible liquids.

Dry, tholeiitic fractional crystallization experiments (Charlier and Grove, 2012) at low-pressure (1-atm) reproduced silicate liquid immiscibility in a broad range of compositions (44–56 wt. % SiO₂, 11.7–17.7 wt. % FeO and Mg# between 29 and 36). They found that the solvus for liquid immiscibility in these natural tholeiitic systems lay below 1020 °C, as had been proposed by Philpotts (1979) and Philpotts (1982). As shown in figure 8, the two-phase region is present at much lower temperatures than had been previously studied experimentally in 1-atm crystallization experiments of more primitive tholeiitic compositions (Grove and Bryan, 1983; Juster and others, 1989; Toplis and Carroll, 1995). The key to discovering the field of silicate liquid immiscibility was to carry out crystallization experiments at low enough temperatures so that the liquid line of descent intercepted the solvus. Charlier and Grove (2012) found, as had prior experimental studies of liquid immiscibility (Watson, 1976; Visser and Koster van Groos, 1979; Nasland, 1983; Bogaerts and Schmidt, 2006), that increasing K₂O, Na₂O, P₂O₅, and TiO₂ contents in the melt also promotes the development of immiscible liquids whereas increasing CaO and Al₂O₃ contents promotes the stabilization of a single liquid (fig. 9).

With a more complete characterization of the extent of natural magma composition space under which liquid immiscibility will occur under dry, low-pressure conditions, Charlier and others (2013) re-examined the major element compositions of tholeiitic basalts and their associated differentiates. The composition gap that is a characteristic of many tholeiitic provinces (fig. 3) coincides with the experimentally determined immiscible liquid field of Charlier and Grove (2012) (fig. 10), and permits a role for large scale separation of silica-rich liquids in the late stages of tholeiitic differentiation. The current perspective is that in volcanic tholeiitic systems the iron-rich, silica-poor liquid is not present because it is too dense to erupt. As we have noted, these Fe + Ti +/− P-rich plutonic products of immiscibility are found in plutonic environments. Just as Bowen pointed out in Chapter 2, the immiscibility process can be difficult to identify because both melts crystallize the same phases with the same composition. Both melts will evolve on the limbs of the solvus and exsolve continuously as the residual liquid changes in response to the removal of crystals. This evolution by fractional crystallization can drive the bulk liquid out of the field of immiscibility back into the single-melt phase stability field. So while it may be hard to
identify, liquid immiscibility certainly occurs in nature, and it plays a role in the latest stages of the tholeiitic differentiation trend.

**Soret Effect**

The Soret effect is produced by chemical diffusion in a melt with a sustained temperature gradient, leading to the development of compositional zoning. Bowen discussed the Soret effect and concluded that it would not be an important process in causing compositional variation in magmas. At the time the magnitude of the Soret effect was not known, and Bowen thought it would be small. Bowen knew that heat diffusion was much more rapid than diffusion of species in silicate melts. He thought that temperature gradients large enough for Soret diffusion to operate would be rare in magmatic systems and would equilibrate before Soret diffusion could have an effect. The magnitude of the Soret effect was first measured experimentally in a lunar melt (Walker and others, 1981) and secondly in a terrestrial mid-ocean ridge basalt (Walker and Delong, 1982). In both compositions the effect of Soret diffusion was discovered to be quite large. The compositional effects were comparable to those created by crystallization over a similar temperature interval and the diffusion of species that led to the compositional gradients were the opposite of those created by crystal fractionation. The Soret species appeared to be similar to network-forming and network-modifying components in silicate liquids. Subject to a temperature gradient, the less dense network-forming components (SiO$_2$, KAlO$_2$, NaAlO$_2$) diffused toward the hot end of the temperature gradient and the more dense network-modifying components (MgO, FeO, CaO) diffused toward the cold end of the thermal gradient (Lesher, 1986).
So while Soret diffusion could operate in temperature gradients in convecting magma chambers, Lesher and Walker (1991) concluded that Soret could not be a major cause of chemical differentiation. Hildreth (1979) initially called upon Soret diffusion to produce the composition zoning observed in the Bishop Tuff, but...
Fig. 10. From Charlier and others (2013). Tholeiitic basalts and their differentiation products are compared to experimental and naturally occurring immiscible melts in ternary composition space. (A) Ternary with CaO and Al₂O₃ plotted at the base and SiO₂/4 at the top. (B) Ternary with CaO and Al₂O₃ plotted at the base and the sum of Na₂O + K₂O + P₂O₅ + TiO₂ at the top. Experimental melts are the ones shown in Figure 9 from Charlier and Grove (2012) and natural immiscible melts are from Charlier and others (2013) and Phillpotts (1982).
withdrew that suggestion in light of Walker and Lesher’s experimental results. Hildreth and Wilson (2007) reinterpreted the zonation as a product of crystal fractionation. Soret diffusion is more likely to occur in rare instances where very high temperature melting processes have occurred leading to silicate melt diffusion rates faster than heat diffusion. Two environments where this might happen are during terrestrial impact melting and the formation of tektites. Delano and Hanson (1996) infer temperatures for tektite reentry into the Earth’s atmosphere of > 3000 °C and find compositional gradients that follow the expected Soret diffusion trends. When lightning strikes lead to the formation of fulgurites, temperatures can exceed 10,000 K (Paseck and others, 2012) and in the right composition target rock, one might anticipate that a Soret compositional gradient could develop. While Soret diffusion may occur in nature, it is only on a very small scale.

CONCLUDING REMARKS

Norman Levi Bowen laid the groundwork for applying experimental petrology to understanding the diversity of igneous rocks. Bowen created the first phase diagrams using his experiments, and established that fractional crystallization of a primary magma would generate a wide range of residual liquid compositions and a wider range of cumulate rock compositions sufficient to explain most igneous rocks. During his time, chemical analyses of liquids could only be made on bulk rocks, forcing the limitation of comparing experiments to relatively sparse glassy igneous rocks. Plutonic igneous rocks, or even sparsely phryic quenched glasses, could contain an unknown amount of crystal accumulation and accordingly would show erroneous liquid lines of descent when graphed, leading Bowen to not consider any chemical evidence from them as trustworthy. All of the rock compositions that matched his glassy criteria were from subduction zones and they universally showed dramatic iron-depletion, silica-enrichment trends. He integrated that knowledge with the presence of abundant granitoids (that is, extremely silica-rich fractionates) and the fact that his experiments resulted in consistent relative crystal appearances from basaltic parental magmas to conclude that there was but one inevitable course of crystal fractionation. Perhaps if the electron microprobe had been available to him so that he could have directly measured more liquid compositions, he might have realized there could be more than one liquid line of descent. But hindsight is 20/20, and regardless that Bowen did not get everything right, his chemically and physically rigorous, experimental approach to petrology has led us down a very fruitful path by providing invaluable tools for expanding our understanding of magmatic systems.

Since Bowen’s tremendous contribution to understanding the evolution of igneous rocks, petrologists have realized that nature is in reality more complex than a single course of fractional crystallization from effectively a single basaltic parental magma. There are a variety of parental magma compositions, which, depending on their geologic context, can undergo different and distinct liquid lines of descents such as a dry tholeiitic trend, a hydrous calc-alkaline trend, and a low-pressure silica undersaturated alkaline trend. Further, significant igneous diversity can come from the other processes Bowen had considered but dismissed. Field and geochemical evidence make it clear that assimilation and magma mixing directly contribute to the variety of igneous rocks. Had Bowen realized that magmatic reservoir/conduit systems are dynamic and episodically replenished, he might have reframed his understanding of magma mixing and assimilation. Comprehensive new experiments and field studies have led to a better understanding of the role of liquid immiscibility. Compositional gradients in liquids are important in magma chambers undergoing replenishment, and Soret diffusion has its place when exceptionally high temperatures are rapidly
imposed, such as during impacts or lightning strikes. Even with all these new discoveries over the last 80 years, fractional crystallization has remained a critical igneous process - the repercussions of which are still fully being explored (for example, Jagoutz and Klein, this issue, and references therein).

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