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The Nature of Magmatism

1.1 Introduction

Direct knowledge of the composition and spatial distribution of Earth's interior material comes largely by magmatic processes spread across the planet. Aside from the bulk composition of the dominant or carrier magma, the inclusion of exotic primocrysts, xenocrysts, xenoliths, and sundry other material carries intimate information on the nature of Earth's interior, including source regions, the plumbing system, and the dynamics of the governing magmatic transport process itself. The ever-present challenge is, once given this evidence, to decipher the complete magmatic process such that the reason for the magmatism and all that it contains can be clearly understood in the true context of the physical and chemical processes that it represents. In the drive to understand the nature of the underlying magmatic source material this is most often attempted purely through geochemistry in an aim to identify distinctive source reservoirs, with much less regard for the actual physical process of the magmatism itself as a primary guide. This is generally also necessitated by the paucity of deeply exposed magmatic systems where the intimate details of the magmatic delivery can be readily deciphered. A singular exception to this paucity is the Ferrar Magmatic System of the McMurdo Dry Valleys that provides an unparalleled example of a complete magmatic intrusive system. From this system truly fundamental insight into hitherto poorly understood magmatic processes can be gained. Hence, a more balanced approach to understanding magmatic source regions is attempted here using everything found in the rocks themselves, especially their spatial distribution.

1.2 Plutonism and Volcanism

Magmatic systems of all sizes and compositions commonly show patterns of individual eruptive centers distributed along otherwise linear tectonic elements.

Island arcs are perhaps the most distinctive, where, along distances of thousands of kilometers, individual volcanic centers, spaced at 50–70 km, have spontaneously operated, off and on, for millions of years (e.g., Marsh, 1976, 1979a, 1979b, 2015). Even oceanic "hot spot" volcanic centers, like Hawaii, show a similar pattern, although here only a single major center predominates at any time (Clague & Dalrymple, 1987). Rift systems are also similar. Although characteristically forming long narrow or piecewise continuous clefts, the magmatism itself, wherever it can be accurately discerned, is in centralized centers. The Great Dyke of Zimbabwe shows this behavior with individual magmatic centers distributed at distances of 70–100 km along a 550 km narrow massive trough, reminiscent of a nascent oceanic ridge (e.g., Worst, 1960; Wilson, 1996). Ocean ridges themselves also show this behavior particularly well (e.g., Schouten et al., 1985; MacDonald, 1986, 2019; Sinton & Detrick, 1992), with magmatic centers operating at discrete intervals along markedly segmented ridges, often existing midway between offsets or other major faults, including Transform Faults. Ascending magma pools at these locations, forming high-level Axial Magma chambers as relatively thin (~100 m) sills, from which magma is dispersed along the ridge. At ridge areas starved of magma, the newly forming oceanic crust is thin and the underlying lithosphere is tectonically emplaced to satisfy the requirements of mass conservation governing the overall flow. All aspects of the ridge, from petrological to biological, morphological, and thermal, are influenced by this segmentation (see the collection of papers in MacLeod et al., 1996). The Ferrar magmatic system of Antarctica may also show something of this pattern of magma ascent and dispersal from highly localized centers, but even more important, occasionally, due to the labors of erosion and relict terrain preservation, a rare magmatic center will reveal the detailed workings of the fully integrated magmatic system itself.

Although all volcanic and near-surface magmatic systems are certainly highly integrated, both physically and dynamically, from source to pluton or volcano, it has proven difficult to gain an intimate understanding of this integration because of limited vertical exposure in Earth's crust. And suites of samples from volcanic and plutonic terrains are individually, in and of themselves, of little help. Volcanic suites sometimes yield a wide range of compositional diversity along with important quenched or incomplete textural development, thereby capturing the element of time, but the spatial context, or provenance, from whence each mass of lava came within the magmatic system, is unknown. There is, no doubt, that a record of the nature and dynamics of the system intimately exists in the pile of lavas simply from stratigraphic position, volume, and composition, but there is no clear way to unravel and relate this accurately to the spatial configuration of the underlying plumbing system and, moreover, how this relates to the process producing the magma.

Plutonic suites, on the other hand, do offer excellent spatial control, but there is no record of the magmatic time series of inputs and outputs leading to establishment and evolution of the final system itself. The rock textures themselves to varying degrees have commonly been seriously thermally annealed, thus obscuring or removing information critical to understanding the history of emplacement and subsequent crystallization. The spatial and temporal record of the dynamics of operation of the system as a whole, relating the vat of magma to its source and to coeval volcanism, has been lost. The all-important initial conditions of the magma that gave rise to the end product are no longer extractable. The prime fundamental questions cannot be answered, namely: What was the style and duration of filling? What was the compositional variation and phenocryst content of the individual magmatic pulses? If phenocrysts and primocrysts were present, where did they come from? Were they sorted prior to injection during ascension or after emplacement into a vat or chamber? And, perhaps above all, how are the dynamics of volcanic and plutonic systems connected?

Purely geochemical petrogenetic scenarios manifestly suffer from this limited understanding by mainly commonly employing, of necessity, only two key end-member regions in considering the production and chemical evolution of magma. These are a source or deep-seated region and a high level, near surface, or supposed magma chamber region. Although it is well appreciated that the intervening pathway or mush column connecting these end points is certainly as important as the endpoints themselves in influencing magma evolution, it has proven elusive to develop a detailed and realistic understanding of this region of magma transfer (e.g., Davidson et al., 2005a, 2005b, 2007). Properties of the magma attributable to the integrated system are thus of necessity collapsed into the endpoints of the system, which reinforces the concept of a virtual magmatic system based on assumed “reservoirs.” That is, the detailed isotopic and trace element suites tend to identify characteristic “source” reservoirs, such as deep mantle plumes, fertile or depleted mantle, each of which may have suffered intricate histories of metasomatism due to subduction or other processes, that through mixing and/or interaction with a primary magma are able to match the observed chemical fingerprints. But the proposed scenarios of magmatic processes are often highly unrealistic. Although this approach is also partly employed herein, it is greatly subordinate to the actual process of magmatism as recorded in the rocks themselves. Here, an age-old dictum is adhered to: The in-situ rocks are the ultimate and final court of appeal.

1.3 Mechanics of Magmatism

To set a framework for all that follows it is convenient to have in mind some specific magmatic systems that may encapsulate some of what has already been

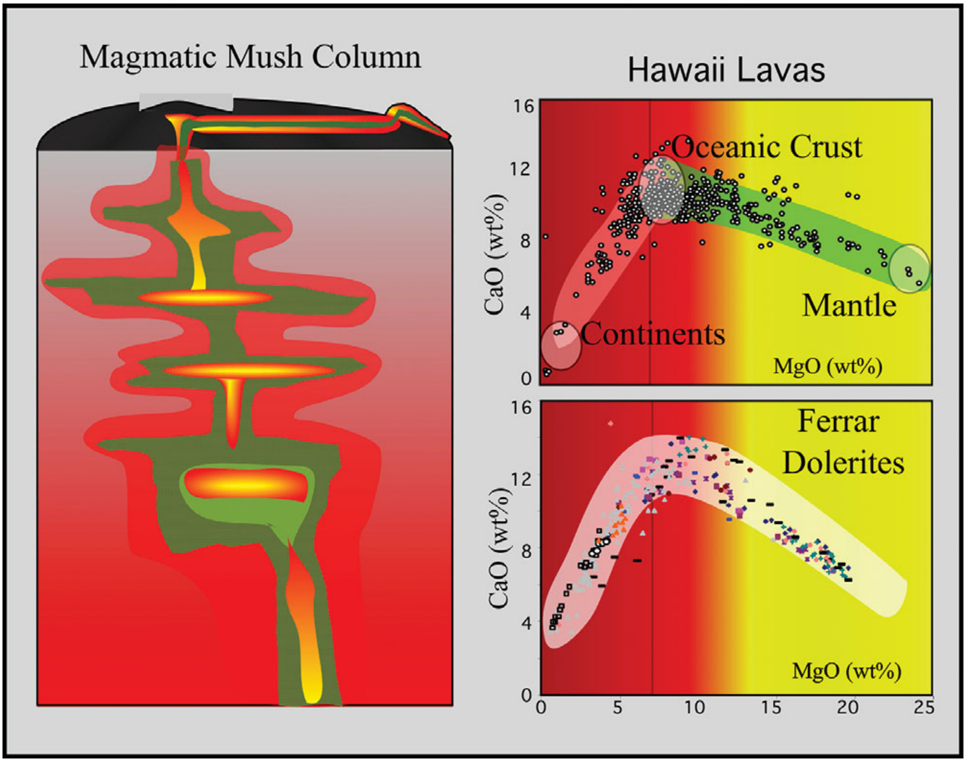

Figure 1.1 A generic depiction of an integrated magmatic system (a Magmatic Mush Column) beneath a volcanic center as a series of high aspect ratio interconnected magma chambers. The color throughout these figures portrays magma temperature, red cooler and yellow hottest; the small black squares amongst a green background depict large crystals of either olivine or orthopyroxene. The spectrum of magma compositions within the system is characterized in a plot of CaO versus MgO (wt.%) for lavas from Hawaii. The first order degree of primitiveness can be gauged by MgO content from typical mantle to oceanic crust to continental material. This variation found within the Ferrar Magmatic System is also shown. The slight difference in slope on the high MgO reflects the role of olivine at Hawaii versus orthopyroxene (Opx) in the Ferrar (after Marsh, 2004).

described. Two magmatic systems serve this purpose: First, a Magmatic Mush Column, which may operate under large centralized magmatic centers like Hawaii (Figure 1.1), and second is an Ocean Ridge Magmatic System, which may exemplify magmatic behavior under active ocean ridges (Figure 1.2).

1.3.1 Magmatic Mush Columns

A Magmatic Mush Column (MMC) is an extensive, vertically interconnected stack of sheets and chambers extending upward through the lithosphere and crust,

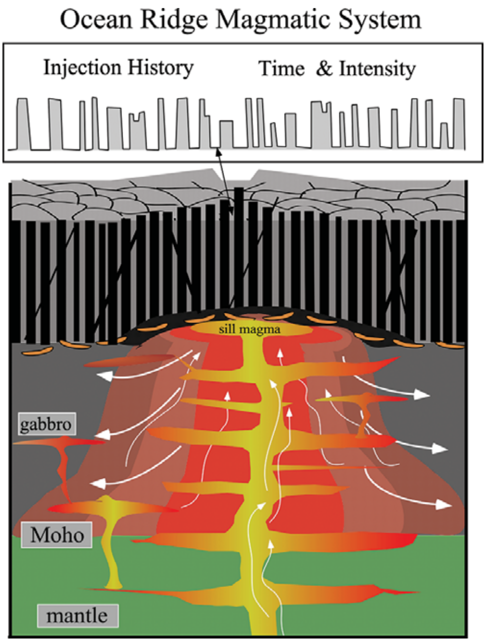

Figure 1.2 The mush column magmatic system at ocean ridges. The system is characterized by a thin sill (Axial Magma Chamber, AMC) capping a vertically extensive system of thin sills and conduits within a massive column of mush. The sheeted dike complex at the top records the history of extraction of magma from the AMC as the plates suddenly pull apart over time periods depicted at the top. Note the small plagiogranite lenses within the upper gabbros formed by solidification front instability (after Marsh, 2015).

capped by a volcanic center (e.g., Marsh, 2004, 2015). Highly fractionated and primitive magmas, and everything in between, may coexist as, respectively, pools of nearly crystal-free magma, crystal-rich magma, thick beds of cumulates, and open or congested (by cognate and wall debris) conduits. Dynamic solidification fronts sheath all system boundaries, advancing inward in response to local geometry, thermal regime, and level of magmatic activity. The eruptive chemical and petrographic nature hinges on the strength and duration of the eruption flux: The stronger and longer the flux, the more crystal-laden and primitive the eruptive. The surficial chemical impression of the deeper nature of the system depends heavily on the temporal dynamics of the system. A system may thus appear petrologically distinct from one episode to the next. The conceptual philosophy behind the measures and processes used to gauge the system strongly colors how the system itself is perceived: “There are many differences and complications in the natural magma in the matter of details, but it is clear that the broad scheme is well understood and that crystallization is the sole control" (Bowen, 1915). That is, Bowenian thinking, for example, yields Bowenian processes.

A key to appreciating the level of physical and chemical integration of a MMC is finding a vertically extensive and intricately exposed system, revealing the spatial connections between lavas, sills, feeders, and ultramafic-layered rocks. It is something of this basic nature that may well be exemplified by the Ferrar dolerites of the McMurdo Dry Valleys, but not entirely. A characterization of the intimate degree of physical and chemical integration of MMC systems is depicted by the basic chemical variation between CaO and MgO of Hawaii and the Ferrar system, as suggested by Figure 1.1. They resemble one another quite closely, even though Hawaiian compositions are controlled by the loss and gain of olivine, whereas the Ferrar is controlled largely by orthopyroxene. The Hawaii compositions all come from lavas whose genetic and spatial origin within the associated MMC is unknown, but, as will become abundantly clear, for the Ferrar the spatial context of each sample is intimately known. Hence the fundamental value of the Ferrar.

This variation between CaO and MgO, in an essential way, depicts the genetic connection between the deeper mantle (MgO ~30 wt.%), the oceanic crust (MgO ~7%), and the highly refined continental crust (MgO ~2%), which is commonly assumed to take place by, at the onset, partial melting followed by fractional crystallization. The fine line at 7% MgO marks the point at the leading edge of the Solidification Front (see Chapter 4) where the phase equilibria changes from single phase saturation, solely olivine or orthopyroxene, to multiple saturation with the appearance of plagioclase and other phases.

1.3.2 Ocean Ridge Magmatism

For much of the past century magma chambers were envisioned to be giant vessels or vats of magma within which crystallization took place throughout. In concert with this classical concept, vast reservoirs of magma were expected at the level of the oceanic crust beneath ocean ridges. When these features were sought using seismic methods, they were not found. Instead, thin (50–100 m), wide (2–3 km) ribbons of magma, or sills, were found (Sinton & Detrick, 1992). This spawned a general model of ridge magmatism more consistent with what is found for systems like the Ferrar, albeit on a smaller scale, and the structure of the oceanic crust is an intimate reflection of the combined process of magmatism in response to plate tectonics.

A general depiction of this system (Figure 1.2) stems from the general form of magmatic sill complexes found in the Ferrar system, in old continental crust, in opiolites (e.g., Nicolas, 1995), and in 3D multi-channel seismic studies in the North Atlantic (e.g., Cartwright & Hansen, 2006), and it is also consistent with what should be expected on a mechanical basis in this tectonic region (e.g., Teagle et al., 2012). This is a magmatic mush column operating under quasi-steady state conditions in response to upwelling and lateral flow (i.e., rifting) due to large-scale mantle convection. The mush column (Figure 1.1) is truncated and stands in partially molten ultramafic mantle rock modally dominated by olivine with subordinate orthopyroxene, clinopyroxene, and plagioclase, with spinel and pyrope-rich garnet at successive higher pressures. At deeper levels (~50–100 km) significant partial melting due to adiabatic decompression (e.g., McKenzie, 1984) forms an anastomosing complex of melt veins and channels concentrating upward into a main mush column stalk with periodic sills (Marsh, 1996; Korenaga & Kelemen, 1998). The axial magma chamber beneath the ridge axis caps the mush column.

The system works through hydrostatic head produced in response to, in effect, suction at the top associated with the abrupt splitting and spreading of the lithospheric plates. From an initial state of slight over-pressuring or near hydrostatic equilibrium, this abrupt motion splits the brittle oceanic crust, withdrawing magma from the underlying axial magma chamber, some of which erupts as pillow lavas, and what is left in the feeder solidifies as a dike. The loss of hydrostatic equilibrium at the head of the system propagates as a pressure pulse downward throughout the system, perhaps partly as solitons, drawing magma upward in the mush column and re-establishing stability. Because all parts of the contiguous ridge plates do not move at exactly the same time and to the same degree, the process of melt motion at depth is certain to be complicated. Magma at some depths may sometimes be transported laterally as it ascends, making its overall trajectory significantly non-vertical.

The intimate time-series history of this process is recorded in the vast sheeted dike complex, which is a unique characteristic by-product of ridge magmatism well known from ophiolites. Because these dikes are random temporal samples of the axial magma chamber, they give throughout time an excellent inventory of the general state of this magma, both in terms of composition and crystallinity. These dikes are typically fine-grained and of low phenocryst content; any phenocrysts are mostly plagioclase. The axial magma chamber or sill is a passive body that experiences bursts of withdrawals followed by recharging from below. Some recharges undoubtedly carry massive amounts of entrained large crystals, principally olivine, which sediment to the floor, undergoing punctuated differentiation immediately upon entering the sill. Layering is thus an indirect reflection of dike formation.

Mid-Ocean Ridge Basalts (MORBS) erupting at the ocean ridges worldwide are tholeiitic basalts, with low K_2O (~0.2 wt.%), modest TiO_2 (~1.5 wt.%), and low and un-fractionated REE (rare earth elements). To first order these basalts are chemically among the most globally uniform of any class of magmas, reflecting the underlying magmatic process of prolonged intimate contact with an extensive mass of solids in the magmatic mush column. In effect, the chemical composition is buffered by the mechanics of the overall process, much as in a household water purification system. This uniformity also reflects the uniformity of mantle composition itself, which has probably not changed drastically over Earth history. That is, at the present rate of ridge magmatism (~20 km^3/year), with about 10 percent melting the mantle will be recycled about once every 5 Ga, which, even allowing for the role of contamination by subduction, suggests the mantle composition has been, to first order, fairly constant throughout Earth history. Due to variations in spreading rate along with slight variations in mantle composition, melting depth and bulk composition cause second order chemical variations (e.g., Klein & Langmuir, 1987).

It is interesting to consider ridge magmatism from the past classical point of view of magma chambers, where primitive (MgO-rich) magma is generated at depth, emplaced in a large vat, and differentiates by crystal growth and settling, generating a long “liquid line of descent” and a large chemical diversity of products from picrites to olivine basalts and tholeiites, and possibly even granites. Instead, there is exceedingly little diversity found at ocean ridges. Even picrites (olivine-rich basalt) are not found at ridges, and arguments have always persisted that if picrites are parental to MORB then why are they never seen? Why don’t they erupt more often, or at all? This is not an uncommon situation in petrologic studies where critically important parts of the hypothesized dynamic puzzle are not seen but are nevertheless postulated to be in a hidden zone or are un-eruptible due to density difficulties or other factors. On the other hand, the fact that critically important magmatic parts of the system are never seen may simply mean that they as actual physical processes don’t, per se, exist as postulated. Instead, a more reasonable process achieves the desired chemical effect, like uniformity. In the present understanding of ridge magmatism, the magmas are chemically fractionated by contact with olivine, and other phases, through prolonged intimate, diffusional, contact within the mush column, not classical crystal fractionation. The lack of presence of an actual massive, 6–8 km thick magma chamber, as postulated on chemical grounds, is replaced by a virtual magma chamber, which is an integrated chemical process taking place over the full extent of the mush column.

This, again, emphasizes the value of being able to interrogate an extensive magmatic system, like the Ferrar system of the McMurdo Dry Valleys, in its natural setting. It is the intimate linking of petrographical and chemical variations with spatial variations that is highly unusual.

1.4 Magmatic Environments

A striking difference between these two magmatic systems is the regional thermal regimes in which they exist. Beneath ocean ridges the entire system resides within a massive thermal upwelling, with high temperature country rock extending outward to great distances; all magmas are, in effect, thermally insulated and can exist in a perpetual steady state almost regardless of size and shape. It is only when magma is evicted from the high-level sill as a dike when severe cooling and quenching takes place.

This is in strong contrast to magmatic mush columns existing in the lithospheric-crustal regimes where the containing country rock is much cooler than the magmatic system (Figure 1.1). Cooling is rapid from all boundaries and there is a constant, if ephemeral, intense competition between active magmatism and progressive solidification. For the system to stay alive for any significant period of time, chilled magma must be periodically replaced by fresh hot magma. There is a wide spectrum of longevity or states of thermal survival measured by the volumetric throughput or ongoing flux of magma through these systems. Large systems, like Hawaii, thermally dominate the lithosphere and can exist for millions of years, leaving a massive thermal imprint on the adjoining lithosphere. Small systems, like those associated with monogenetic volcanism, may only evade thermal death for a thousand years or so. Magmatism associated with Gondwana rifting begins as small weak systems sometimes die when rifting is aborted, and with successful rifting become massive ocean ridge systems. Perhaps the most important, most telling, and valuable systems are those that become strong and well developed but then, due apparently to tectonic manifestations, fade. Yet, besides establishing a mature plumbing system, they impose an intense thermal imprint on the crust, sometimes leading to extensive remelting and reworking of the entire adjacent crust. It is these systems that reveal much of the intimate workings of mature magmatic systems. This is what is exhibited in the McMurdo Dry Valleys.