PROCESSES OF MAGMA EVOLUTION AND MAGMATIC SUITES

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Summary

Magmas are formed by partial melting of silicate rocks either in Earth's mantle or the continental crust (see *Igneous and Metamorphic Petrology*). Primary magmas from Earth's mantle are basaltic in composition, and form the oceanic crust and part of the continental crust. Through the history of Earth, mantle magmas and their differentiation products represent juvenile additions from mantle to crust, and thus the formation and differentiation of magmas is the underlying process in the formation of the continents on which we live.

Magma composition, in particular the contents of silica and volatile compounds (mostly water and CO_2) will determine the physical properties of the melts, such as density and viscosity. These factors play a key role in the processes of segregation and ascent of magmas. Magmas either erupt directly to Earth's surface, or they may accumulate in magma chambers. Cooling and crystallization will change their chemical composition,

and—in turn—their physical properties. Enrichment in volatiles and reduced density will eventually result in the eruption of these chemically differentiated magmas.

Magma chambers have sizes between 1 km and large molten bodies of pluton size (several tens of km), which have been thought to exist from the processes and products of magmatic differentiation and direct geophysical measurements, as well as from the occurrence of solidified analogues exposed by erosion.

The composition of magmas differentiated from primary melts depends on the initial composition, which is ultimately determined by the source and process of partial melting in the mantle (see *Melting in the Mantle).* Among major elements, the ratio between alkalis and silica has a key role in determining the type of magma series: silica-saturated basaltic magmas evolve to rhyolites, alkali basalts differentiate to trachytes, and undersaturated basaltic magmas (basanites, foidites) form phonolites. Differentiation processes determine changes in major elements (for example, enrichment in Si, K), as well as enrichment or depletions in minor and trace elements. In consequence, magma formation and differentiation leads to the enrichment of certain elements in Earth's continental crust that are important nutrients for plants and animals.

1. Introduction

Earth formed from the cold accretion of cosmic matter about 4.55 billion years ago. Since then it has differentiated into a Fe-rich core, a mantle rich in Mg, Si, and O with only a little Ca, Al, Fe, and other minor elements, and the continents on which we live. While the continents have grown in size since about 4 billion years, the oceanic crust is formed continuously and is destroyed within about 200 million years by subduction (see *Mantle Dynamics and Plate Tectonics*). Magmas from the mantle play an important role in the evolution of the Earth and its continents.

Magma genesis, the formation of magma chambers in the crust and the processes that change the compositions of magmas en route to the surface, are important aspects of the Earth system. Magmatic processes and the evolution of magmas throughout geological history have shaped the globe by forming the continents and providing nutrient elements in abundances that have made them important in the metabolism of plants and animals. Without magmatism and the chemical differentiation of magmas, life as we know it would not be possible. Therefore, it is important to understand the principles of such basic processes and to place them into the context of other processes and parameters that were prerequisites for the evolution of sustained life on Earth.

2. Melting in Earth's Mantle

2.1. What Causes the Melting of Rocks and Formation of Magmas?

As Earth's mantle is a mixture of solid silicate phases, melting takes place within a melting interval between the solidus (when all is solid) and liquidus (all is liquid). However, geophysical measurements indicate that Earth is generally solid, down to the outer core. Melting in the mantle and magma formation must thus involve special circumstances such as decompression or a reduction in the melting point of rocks (see

Figure 1; also *Igneous and Metamorphic Petrology* and *Melting within the Mantle*). Decompression can be the result of active mantle upwelling such as in plumes, or passive upwelling when the lithospheric plates are extended and separated (see *Mantle Dynamics and Plate Tectonics*).

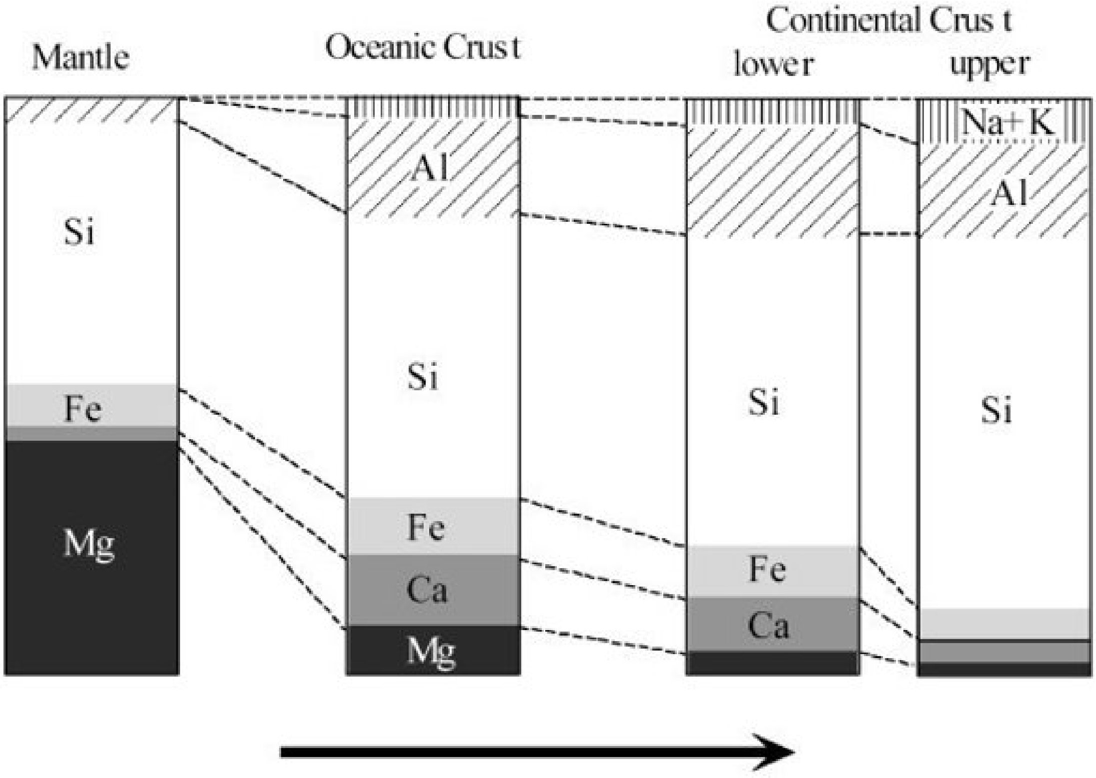

Figure 1. Distribution of elements between mantle, oceanic and continental crust

A direct relation exists between the amount and rate of decompression of mantle material and the degree of melting (see *Melting within the Mantle*). Also the composition, in particular the presence and amount of water-bearing minerals in the mantle rocks, will change mantle-melting behavior. Mantle magmas are of basaltic composition (s.l.). As the degree (and pressure) of melting varies, so the major and trace element composition changes.

Melting by heating is not a general process in the mantle, and can only be found in relatively rare cases within the continents. There, crustal stacking by tectonic processes may result in internal heating from the decay of radioactive elements (mostly K, U, Th), and melting takes place some tens of millions of years after the crust had been thickened (see *Ultrametamorphism and Crustal Anatexis*).

Alternatively, crustal rocks can be heated to partial melting by advective heat transport through mafic magmas underplating crustal rocks, or delamination of the mantle part of the lithosphere and the superposition of the hot asthenosphere to the base of the crust. Slow heat conduction/production results in a long time lag—in the range of millions of years—between the tectonic process and the actual melting.

2.2. Partial Melting and its Effect on Major and Trace Elements

Partial melting will result in the distribution of elements between melt and residue depending on first, the phase relations of melting at the given compositions and physical conditions for the major elements, and second, ionic radius, charge, and the lattice sites present in the residual mineral phases for the trace elements. In effect, major elements such as Si, Fe, Al, Ca, K, and Na will be enriched, and Mg retained in the solid (Figure 1). Those trace elements that are incompatible in size (too large) or charge (lower or higher than 2+) with the residual minerals will also be enriched (Figure 2) (see *Behavior of Trace Elements in Magma Genesis and Evolution*; *Melting within the Mantle* and *Igneous and Metamorphic Petrology*).

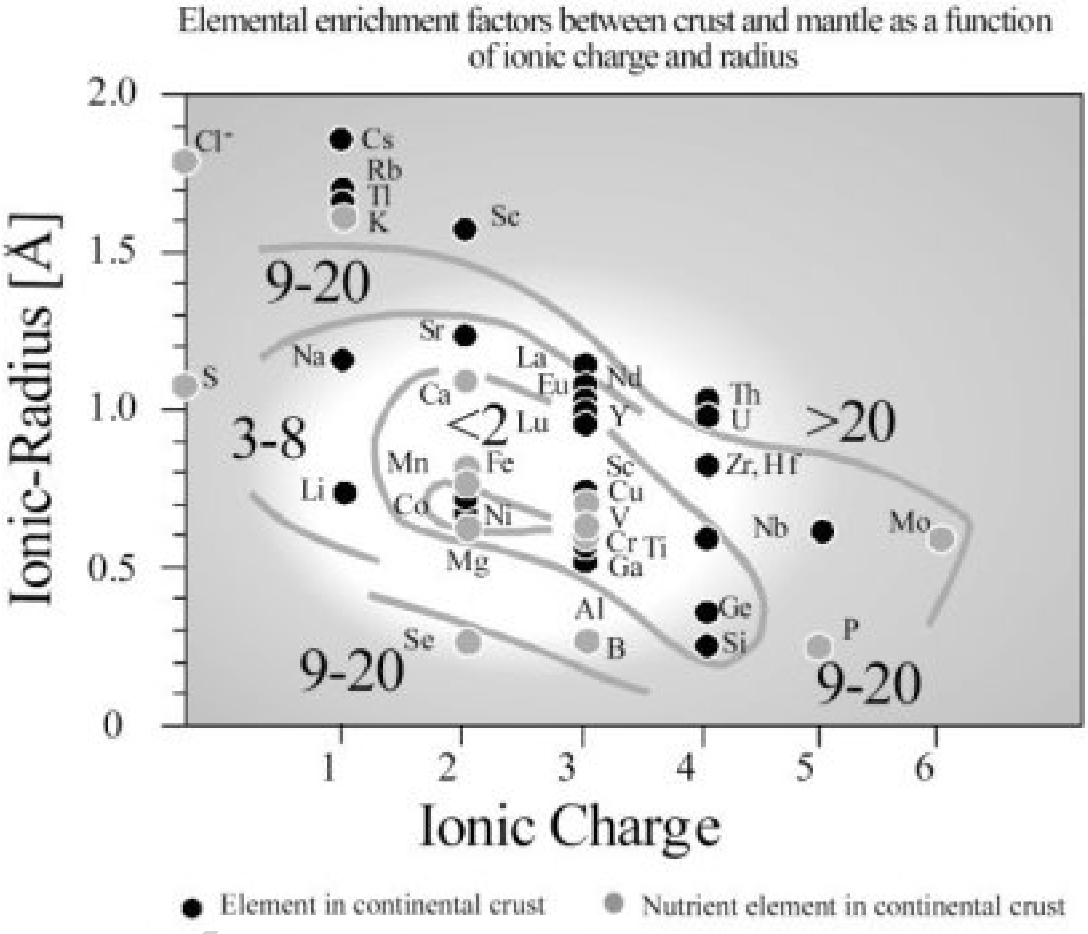

Figure 2. Enrichment of trace elements in the continental crust relative to their abundance in mantle rocks as a function of their charge and ionic radius

2.3. Types of Primary Magmas

Different degrees of partial melting will result in different magma compositions. At small degrees of melting, highly incompatible elements will be strongly enriched in the melt, but further melting will dilute this early enrichment. Therefore, the timing of melt segregation and ascent will determine the composition. In addition, the pressure of melting and the presence of accessory, water-bearing mineral phases in the source rock will cause distinct types of magmas, which are typical for certain geological settings (Figure 3):

Tholeiites are the product of large degree melting (10–15%). They form as midocean ridge basalts (MORB, Figure 3) where mantle material is welling up passively as a result of the divergent motion of the lithospheric plates. In tectonic settings where the hot, actively upwelling mantle melts (such as below Hawaii), tholeiites form as ocean island basalts (OIB). Their trace element patterns are distinctly different (see *Igneous and Metamorphic Petrology*). Tholeiite magmas—once crystallized—thus comprise the bulk of the ocean floor, which makes up 70% of Earth's crust. The amount of magma produced annually by this process is in the order of 10 km^3. This figure was undoubtedly higher earlier in Earth's evolution, when internal heat production from the natural radioactive decay of elements was still strong.

During its history, the evolution of Earth has been interrupted by gigantic eruptions of tholeiitic magmas, measuring millions of km^3 (achieved in a relatively short time span of 1 million years or less) and concentrated in particular regions of the globe. Such continental flood basalts (CFB) or large igneous province (LIP) events have been related to the ascent of large mantle plumes, which represent hot upwelling mantle rocks possibly from the core–mantle boundary. Once mantle plumes reach the base of the crust, spread and undergo decompression below the solidus, causing the formation of large volumes of tholeiitic magmas in short geological times. Examples of flood basalt provinces are the Deccan trapps in India, Karoo basalts in southern Africa, and the Parana basalts in South America.

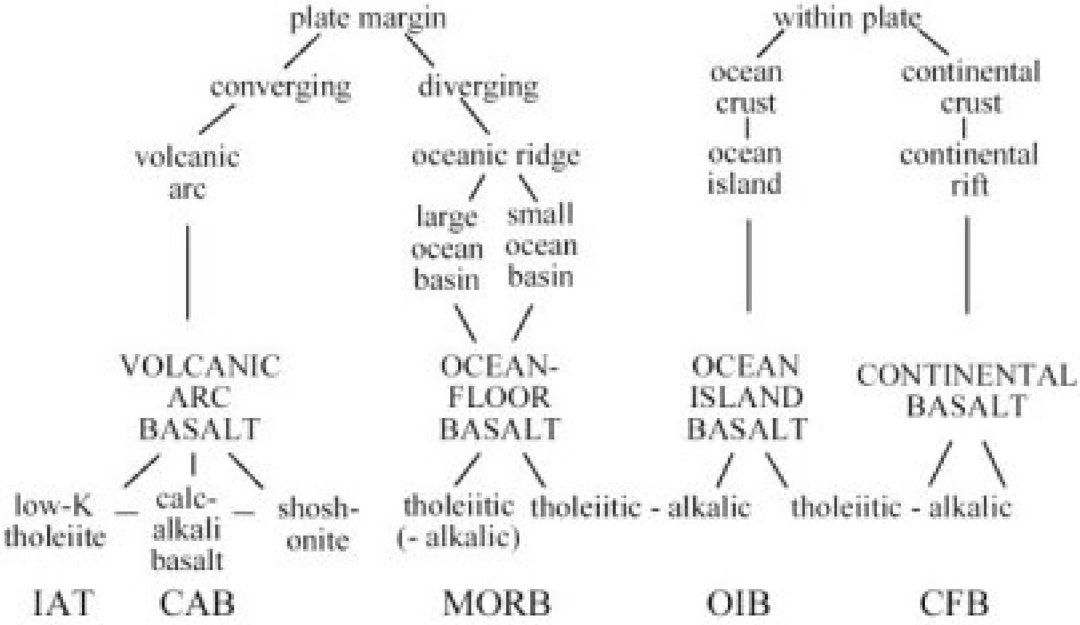

Figure 3. Types of primary magmas and their tectonic setting

Another type of tholeiitic basalt magma forms in primitive island arc subduction settings. While their major element composition is similar to those of intra-plate and divergent-plate tholeiites (MORB, OIB-tholeiites, see above and Figure 3), the trace element pattern of these island arc tholeiites (IAT, Figure 3) is again distinctly different. They show the additional chemical component introduced into the magma source by the dehydration of the subducted oceanic plate (see *Role of Fluids in Igneous Petrogenesis* and *Igneous and Metamorphic Petrology*).

Calc-alkaline basalts (CAB): form along converging plate margins above subduction zones, where the crust is thicker and the magma generation rate generally lower. Calc-alkaline basalts are silica oversaturated and have a higher potassium content than tholeiitic basalts.

Alkali basalts, basanites, and more alkaline mafic magmas: form from smaller degrees of partial melting, and often their isotopic composition demands a long-term depleted mantle source, whereas their trace element contents (high in incompatible elements) suggest a geologically recent enrichment in the source. Therefore, the source of alkali basalts (and more alkaline magmas) has been considered to contain a water-bearing, trace element-enriched metasomatic phase (amphibole and/or phlogopite).

Alkaline basalts occur in intraplate settings, such as ocean islands, continental volcanic fields, and rift systems. An example of an oceanic setting is the Hawaii archipelago, where a much smaller volume of alkali basalts overlies large tholeiitic lava piles.

The interpretation is that the main phase of plume melting beneath the Hawaiian hotspot gave tholeiitic basalts, whereas in the waning stage, as the plate has moved over the melting region, the melting degrees and the magma production rates are smaller. Consequently, the magma composition changes to alkaline basalts, and the likelihood of magma storage, cooling, and differentiation increases. Therefore, the Hawaiian alkali basalts are typically associated with differentiated magmas such as mugearites and trachytes.

Alkaline basalts and more undersaturated magmas on continents are typically related to regions where lithospheric extension has created intra-plate rifts. The African Rift Valley is a prime example.

There are a number of more *exotic primary magmas*, usually highly alkaline primary magmas, which are very small in volume but have a paramount petrological and geodynamic importance. These encompass *lamproites* and *kimberlites*, which almost exclusively are erupted in continental settings. These magmas are characterized by a variable degree of silica undersaturation and a high potassium contents. In detail, there are different types of these potassic magmas.

Those that erupted from and through very old lithosphere, such as in southern Africa and Australia, carry diamonds, which are economically important. Finally, the only occurrences on Earth of magmas that are not formed from molten silicate (with the exception of rare sulfur melts at Poas Volcano in Costa Rica) are *carbonatites*. The origin of carbonatites is still an enigma. Some apparently form from direct melting of metasomatized mantle rocks, while others form from silicate–carbonate melt immiscibility. An example of a carbonatite center is the active volcano of Oldoinyo Lengai in Tanzania.

2.4. Accumulation and Ascent of Magma

Melts—once formed—can segregate and ascend because of surface tension and buoyancy. The critical parameters determining whether melts actually will accumulate and ascend as discrete magma bodies are the degree of partial melt and the wetting angle between melts and source mineral grains, which depends on the difference in surface energies between the residual mineral grains and the silicate melt. Liquids formed by small degrees of partial melting will only segregate if the wetting angle is low enough to assure an interconnecting network of melt. At small degrees of partial melting, melt extraction will only be possible at wetting angles between 0 and 60°. Once an interconnecting system of melt has formed and a critical threshold of partial melting has been reached, the migration of melts will change from porous flow by compaction to a channelized flow regime. Presently, there is no consensus on what the lower limit of melt extraction is (< 1 or > 5%).

Records of channelized melts can be seen as veins in mantle peridotite, where such mantle rocks have been uplifted to Earth's surface by tectonic processes.

Once melts have accumulated, they will ascend by a fracture-controlled process, and form melt-filled dikes that can reach the surface as fissure eruptions. The ascent in the mantle will be mostly governed by magma buoyancy, which will be determined by the difference between the densities of the magma and the surrounding rocks. Once a magma reservoir has formed, magma can ascend through cracks driven by hydrostatic pressure. During the upward flow, cooling will take place, and at critical values of ascent rate, temperature contrast and dike width, the dike can freeze. Also, whenever the density of the rocks changes, such as at the boundary between mantle and crust, buoyancy will be reduced and magmas can accumulate. During ascent, storage, and cooling, magmas will start to crystallize and thus change their chemical composition.

3. Magma Chambers

Only a few magmas reach the surface without storage in intermediate reservoirs. There is ample evidence for the existence of such magma chambers. Large shield volcanoes have shown by detailed tilt measurements to become inflated prior to an eruption (for example, Hawaii), and the absence of earthquakes in certain crustal volumes suggests the presence of reservoirs of molten rock at depth. Direct geophysical proof of magma chambers also exists from active reflection seismic measurements. The geological record is most compelling. Large eruptions of ignimbrites, some of a volume of several thousands of cubic kilometers, have left circular depressions on Earth's surface (calderas) from the volume deficit they left after the evacuation from the magma chamber. Many eroded intrusions also document the existence of large magma chambers within the crust, from a few hundred meters to often many tens of km in size. One of the largest known magma chambers is the Bushveld intrusion in South Africa, which evolved to a size of more than 1 million cubic kilometers by repeated intrusion. The Bushveld intrusion hosts a large ore deposit for Ni and metals of the platinum group of elements.

3.1. Cooling, Convection, Crystallization, and Differentiation

Once magma has accumulated at its level of neutral buoyancy, it will undergo cooling, starting from the contact with wall rocks. The result will be partial crystallization. Crystals will nucleate in the melt and an assemblage of one or more different mineral phases will start to crystallize. As these crystals have a composition different from the host melt, the composition of the remaining melt will change. Physical separation of these crystals from the melt will result in the chemical differentiation of the magma.

One process of crystal separation from parent melt is gravitational settling. However, at high silica contents and small crystal sizes, gravitational settling as governed by Stoke's law will not be effective; under certain circumstances plagioclase crystals may actually float in basaltic magma chambers.

Alternatively, compositional boundary layer convection has been proposed, where crystals form at the cooler magma chamber walls and the remaining differentiated melts become buoyant and rise to the top of the magma chamber. This process has been favored to explain compositional layering, which is sometimes observed in pyroclastic deposits from zoned magma chambers.

Other differentiation mechanisms are compaction of crystal mush at the cumulate base of magma chambers, and—less efficient—diffusion in the melt phase and transport in a volatile phase. These latter processes occur only in highly differentiated, volatile, and alkali-rich magmas. Finally, liquid immiscibility of carbonate or sulfide melts from silicate magmas explains the occurrence of carbonatites from evolved alkaline magmas (see above) and sulfide accumulations in mafic magma chambers (Bushveld Intrusion, see above).

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Biographical Sketch

Gerhad Woerner, born 1952 in Kassel (Germany), received his Master's and Ph.D. degrees at the University of Bochum. During his Ph.D., he spent one year in the United States, working with the USGS. During this time, he directly witnessed the May 18 1980 Mt. St. Helens eruption as a guest member of the USGS team. He returned as a research associate to Bochum where he received his Ph.D. in 1982 with a thesis on the geochemical evolution of the Laacher See magma chamber.

Since then he has worked on volcanism and the origin and differentiation of magmas in varied tectonic settings. With his students he did research on subduction zone magmas and the evolution of the Central Andean crust in northern Chile. In Costa Rica they studied the consequences of slab window formation and in Kamchatka his group performed a detailed across-arc traverse to unravel the effects of magma formation along the downgoing slab. In the Ross Sea area (Antarctica) his study object was intra-plate rift magmatism and their xenoliths. In addition, he has published on the formation of Variscan granites and Jurassic Ferrar flood basalts in Antarctica.

His studies led him to the University of Mainz and to various visits of postdoctoral research at the Lamont Doherty Earth Observatory. He became a full professor of Geochemistry at the University of Goettingen in 1993. He has received several prizes for his work, including the renowned Leibniz-Prize of the German Science Foundation. He is a member of a number of national and international committees and presently serves as a Member of the Scientific Board of the UNESCO/ IUGS sponsors of the IGCP–Program.