



The mixing of magmas in plutonic and volcanic environments: Analogies and differences

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ABSTRACT

Magma mixing processes have been widely recognized in both the plutonic and volcanic environments, but the quality and quantity of information that can be extracted from the two environments are substantially different. Understanding the advantages and limits associated with the study of plutonic and volcanic rocks is essential to establish precise methodological approaches to build the most complete conceptual model by merging information from these two complementary igneous environments.

In this work we review magmatic interaction processes in the plutonic and volcanic environments by considering several aspects of these geological phenomena. In particular, we first briefly report on the structural and geochemical evidence for magma mixing in both plutonic and volcanic rocks, with the aim to provide a general picture of this natural phenomenon. Successively, we discuss some recent results about magma mixing achieved using the concepts from Chaos Theory and discuss their potential impact on magma differentiation. Finally, we attempt to build a general picture of this igneous process by merging present-day information from both the plutonic and volcanic environments. It emerges from the general picture that the time spent by the magmatic system in the molten or partially molten state is the crucial factor for the preservation of the fingerprints of magma mixing in the two environments. We propose a conceptual model that may be useful to understand what kind of information we can obtain from volcanic and plutonic rocks and, ultimately, to maximize our knowledge about magma mixing.

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1. Introduction

The development of scientific hypotheses is constituted by different evolutionary stages. The first stage is characterized by the observation of a phenomenon that is considered worth noting, because it goes beyond the standard idea that a scientific community has developed about a natural system. The second stage, that necessarily requires recognition from the scientific community, is based on measurements and modeling to quantify, reproduce, and understand the new phenomenon. Therefore, it can be said that the *infancy* of a hypothesis is essentially characterized by observation, whereas its *maturity* is represented by quantification. The infancy and maturity stages are connected by an intermediate stage in which it is realized that observation is not enough to fully understand the phenomenon and, thus, it is necessary to shift to more evolved stages.

In 1851, the chemist Robert Bunsen (Bunsen, 1851) published a pioneering work suggesting that mixing of two magmas might explain most of the compositional variability observed in igneous rocks. Several geologists strongly criticized this work and the magma mixing idea was rejected and remained in disrepute for almost one

century (see e.g. Wilcox, 1999 for a historical overview). The acceptance of fractional crystallization as the new paradigm for explaining magma differentiation (Bowen, 1915) strongly contributed to bury the magma mixing idea in the graveyard of forgotten hypotheses. However, around the 1950s the magma mixing concept resuscitated energetically as the result of the indisputable evidence documented in the rocks (e.g. Bailey and McCallien, 1956, Wager and Bailey, 1953). After an infancy of about 20–25 years, in which a number of observations have been recorded (e.g. Walker and Skelhorn, 1966, Yoder, 1973), this process passed through an intermediate stage (e.g. Huppert and Sparks, 1980, Kouchi and Sunagawa, 1985, Oldenburg et al., 1989, Sparks and Marshall, 1986, Turner and Campbell, 1986, Vernon et al., 1988) that only recently evolved toward maturity (e.g. Bergantz, 2000, Jellinek et al., 1999, Petrelli et al., 2011). Support to these considerations is given in Fig. 1, in which are reported the number of articles published in the literature about magmatic interaction processes from 1950 to 2010. Data used to build the graph were collected from the database GeoRef during October 2011 (<http://www.georef.org>). In particular, for each five-year period, the expressions “magma mixing”, “magma mixing modeling/experiments/simulations” have been chosen to query the database. The graph shows that, starting from 1980s the number of papers on magma mixing increases exponentially reaching the value of approximately 900 in 2005–2010. On the contrary, the number of papers focused on

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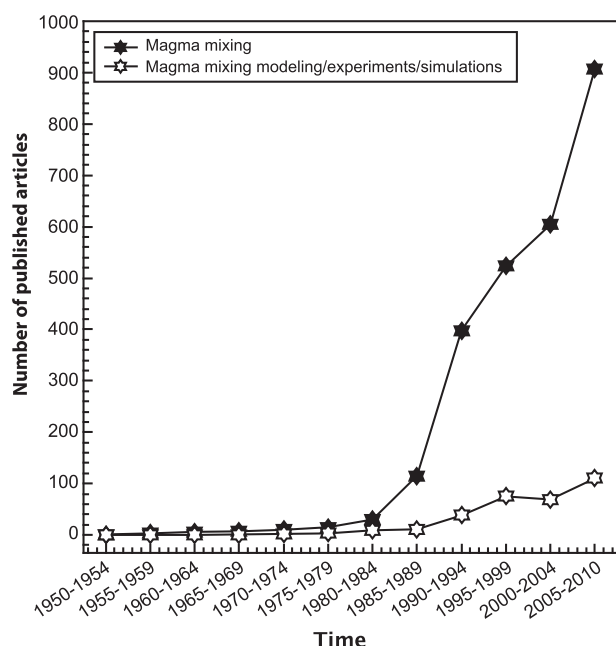


Fig. 1. Graph showing the number of articles published on magma mixing processes from 1950 to 2010. For each five-year period, the expressions "magma mixing", "magma mixing modeling/experiments/simulations" have been used to query the database. Source data: GeoRef, October 2011 (<http://www.georef.org>).

modeling, experiments or simulations does not grow at the same rate: it remains close to zero up to the beginning of 1990s and, then, it slowly increases indicating that the maturity stage may take a long time to be fully developed. Nevertheless, reaching such a maturity stage is very likely to place magma mixing in the first position among all differentiation processes acting to produce compositional diversity in igneous rocks.

A plethora of works suggested that the mixing of magmas can play a very important role in both modulating the compositional variability in igneous rocks (e.g. Blundy and Sparks, 1992, De Campos et al., 2004, Wiebe, 1994) and triggering of highly explosive volcanic eruptions (e.g. Leonard et al., 2002, Murphy et al., 1998, Sparks et al., 1977). However, despite the indisputable importance of magma mixing in modern igneous petrology and volcanology, and the progresses in experimental and numerical modeling strategies (e.g. Bindeman and Perchuk, 1993, De Campos et al., 2011, Perugini et al., 2003a, Zimanowski et al., 2004), we are still far away from understanding even the basic physico-chemical mechanisms associated with this natural phenomenon and their potential impact upon our understanding of igneous systems.

Mixing processes have been widely recognized in both the plutonic and volcanic environments, but the quality and quantity of information that can be extracted from the two environments are substantially different. Understanding the advantages and limits associated with the study of plutonic and volcanic rocks is essential to establish precise methodological approaches to build the most complete conceptual model by merging information from these two complementary igneous environments.

In this paper, we review magmatic interaction processes in the plutonic and volcanic environments by considering several aspects of these geological phenomena. In particular, we first briefly report on the structural and geochemical evidence for magma mixing in both plutonic and volcanic rocks, with the aim to provide a general picture of this natural phenomenon. Successively we discuss some recent results about magma mixing achieved using the concepts from Chaos Theory and discuss their potential impact on magma differentiation. Finally, we attempt to build a general picture of this

igneous process by merging present-day information from both the plutonic and volcanic environments. The aim is to provide a conceptual model that may be useful to understand what kind of information we can obtain from these two igneous environments and, ultimately, to maximize the knowledge about magma mixing processes.

2. What is magma mixing?

It has become an accepted practice to apply the term *magma mingling* to indicate the process of acting to disperse physically (no chemical exchanges are involved) one or more magmas within a host magma, whereas the term *magma mixing* indicates that the mingling process is also accompanied by chemical exchanges (e.g. Flinders and Clemens, 1996). Unfortunately, such a jargon is not consistently used in the literature and this produced some misunderstanding. Although it is not always easy to clearly discriminate between the two processes, we believe that mingling is a quite rare process in nature. In fact, as mingling proceeds, the contact area between magmas strongly increases leading to an increasing probability for chemical exchanges to occur. Therefore, unless it can be clearly demonstrated that no chemical exchanges occurred between magmas, the term *mixing* should be preferred. In the rest of this work we will rely upon this consideration and use the word *mixing*.

It has been widely documented that magmas can mix efficiently only when their rheology is similar (e.g. Bateman, 1995, Poli et al., 1996, Sparks and Marshall, 1986). Such physical conditions can occur when: (a) magmas have a similar rheology from the beginning of the interaction process, and (b) different magmas achieve a similar rheology in response to evolutionary processes (e.g. Poli et al., 1996, Sparks and Marshall, 1986). Since here we are interested in discussing the development of the mixing process, in the rest of this work we assume that magmas are in rheological conditions allowing the mixing process to happen, without incurring potential problems related to rheological barriers. The discussion about the influence of rheological properties on promoting or inhibiting the mixing process can be found in the works cited above.

The mixing of magmas is a process that can virtually occur at any stage in the life span of a magmatic system and it does not necessarily require the presence of end-members generated from different sources (e.g. mantle- and crust-derived melts; Fig. 2a). In fact, mixing processes can take place whenever chemical gradients are present in the magmatic system. This implies that mixing processes may affect petrological processes such as fractional crystallization, assimilation and partial melting, which inevitably cause both chemical and temperature gradients. Fractional crystallization tends to occur along the cooler walls of magma chambers or conduits and depletes the magma in those elements, which are incorporated into the crystals inducing compositional gradients between the core and the more external portions of the magmatic mass (Fig. 2b). A further scenario is the assimilation of country rocks, in which volumes of magma close to the walls would attain a different chemical composition than the core region (Fig. 2c), generating compositional gradients and, potentially, being affected by mixing. Regarding partial melting, if there is a temperature gradient in a partially molten zone, compositional gradients would be also produced (Fig. 2d). Melts formed at small melt fractions are more enriched, for instance, in Rare Earth Elements (REE) and other incompatible elements than those formed at larger melt fractions. Such compositional gradients are the prerequisite for triggering mixing processes. In addition, in any petrologic configuration in which melts with different compositions can be generated it is also very likely that magmas are transported to different crustal levels. During this process the different melts can crosscut their mutual trajectories en-route to the surface and undergo magma mixing (Fig. 2e). It is also possible that all the above processes may act together, strongly amplifying the effect of mixing and inducing a considerable inhomogeneity in magmatic systems.

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