Magma Mixing: History and Dynamics of an Eruption Trigger

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Abstract

The most violent and catastrophic volcanic eruptions on Earth have been triggered by the refilling of a felsic volcanic magma chamber by a hotter more mafic magma. Examples include Vesuvius 79 AD, Krakatau 1883, Pinatubo 1991, and Eyjafjallajökull 2010. Since the first hypothesis, plenty of evidence of magma mixing processes, in all tectonic environments, has accumulated in the literature allowing this natural process to be defined as fundamental petrological processes playing a role in triggering volcanic eruptions, and in the generation of the compositional variability of igneous rocks. Combined with petrographic, mineral chemistry and geochemical investigations, isotopic analyses on volcanic rocks have revealed compositional variations at different length scales pointing to a complex interplay of fractional crystallization, mixing/mingling and crustal contamination during the evolution of several magmatic feeding systems. But to fully understand the dynamics of mixing and mingling

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processes, that are impossible to observe directly, at a realistically large scale, it is necessary to resort to numerical simulations of the complex interaction dynamics between chemically different magmas.

1 Magma Mixing: A Brief Historical Overview

One of the first investigations on magma mixing recorded in the literature is the work of the chemist Bunsen (1851), a scholar at the University of Heidelberg who published research on the chemical variation of igneous rocks from the western region of Iceland. Through chemical analyses Bunsen highlighted that the linear correlation between pairs of chemical elements in binary plots in those Icelandic rocks was the consequence of "simple" binary mixing between two magmas with different chemical composition. Bunsen published this data and, for the first time, magma mixing was taken into account to explain the chemical variation of a suite of igneous rocks. This idea triggered a strong critical reaction from the geological community; the strongest opposition coming from Wolfgang Sartorius Freiherr von Waltershausen an expert on the Iceland and Etna volcanic areas at that time. He mostly argued against the method used by Bunsen of averaging rock analyses to calculate the starting end-members that eventually took part in the mixing process. Sartorius criticized not only the arbitrary choice of the end-members but also disliked the idea of Bunsen of an extensive layering of felsic/mafic rocks and magmas beneath Iceland.

Since the beginning of the 20th century, the experimental and thermodynamic work of Norman L. Bowen (e.g., Bowen 1928) has had a profound influence upon the way petrological processes and igneous differentiations are conceived. The conceptual model of fractional crystallization was firmly established as the most fundamental petrological process for generating the diversity of igneous rocks and remained so for many decades. Although Bowen did not explicitly deny the possibility of magma mixing, he reinterpreted field evidence of magma mixing rather as immiscibility of liquids (e.g., Bowen 1928). In 1944, Wilcox published a work on the Gardner River complex (Yellowstone, USA; Wilcox 1944) which is now considered a milestone for evidence of magma mixing, even if at that time it received strong comments from Fenner and remained one of the few papers on the topic. Only in the 1970's geoscientists started to deeply investigate magma mixing, recorded as a plethora of unequivocal evidence in both plutonic and volcanic rocks, as a major petrogenetic process (e.g., Eichelberger 1978, 1980; Blundy and Sparks 1992; Wiebe 1994; Wilcox 1999). Since the first hypotheses about the origin of mixed igneous rocks (e.g., Bunsen 1851), plenty of evidence of magma mixing processes, in all tectonic environments, throughout geological time, has accumulated in the literature allowing this natural process to be defined as a fundamental petrological process playing a key role in the generation of the compositional variability of igneous rocks and as a major process for planetary differentiation (e.g., Eichelberger 1978, 1980; Blundy and Sparks 1992; Wiebe 1994; De Campos et al. 2004; Perugini and Poli 2012; Morgavi et al. 2016).

2 Magma Mixing: Field Evidence

It is common practice in the petrological community to split magma mixing into two separate physico/chemical processes: (i) mechanical mixing (also referred to as "magma mingling"), by which two or more batches of magma mingle without chemical exchanges between them, and (ii) a chemical mixing (also referred to as "magma mixing") triggered by chemical exchanges between the interacting magmas in which elements move from one magma to the other according to compositional gradients continuously generated by the mechanical dispersion of the two magmas (e.g., Flinders and Clemens 1996). Physically, "magma mingling" is mainly controlled by the viscosity contrast between the two magmas; decreasing of the viscosity contrast results in progressively more efficient mingling dynamics (e.g., Sparks and Marshall 1986; Grasset and Albarede 1994; Bateman 1995; Poli et al. 1996; Perugini and Poli 2005). Chemically, "magma mixing" is driven by the mobility of chemical elements in the melt fractions of the two magmas (e.g., Lesher 1990; Baker 1990). Linear variations in inter-elemental plots for a set of rock samples have long been considered as the sole evidence for the occurrence of magma mixing (e.g., Fourcade and Allegre 1981).

The adoption of the above conceptual models led to the common practice of applying the term magma mingling to indicate the process acting to physically disperse (no chemical exchanges are involved) two or more magmas, whereas the term magma mixing indicates that the mingling process is also accompanied by chemical exchanges. Although such a conceptual approach may allow us to simplify the complexity of the magma mixing process and make it more tractable from the petrological point of view, unfortunately such terminology is not consistently used in the literature and this causes some misunderstanding. Although it is not always easy to clearly discriminate between the two processes, mingling is quite a rare process in nature as physical dispersion and chemical exchanges must occur in tandem during magma mixing processes (e.g., Wilcox 1999; Perugini and Poli 2012).

The most common evidence for magma mixing in igneous rocks is the occurrence of textural heterogeneity; the processes responsible for this have been discussed extensively in many works in the last decades (e.g., Eichelberger 1975; Anderson 1976; Bacon 1986; Didier and Barbarin 1991; Wada 1995; De Rosa et al. 1996; Ventura 1998; Smith 2000; Snyder 2000; De Rosa et al. 2002; Perugini et al. 2002, 2007; Perugini and Poli 2005, 2012; Pritchard et al. 2013; Morgavi et al. 2016).

In order to provide possible classification of magma mixing structures, the evidence of mechanical mixing in igneous rocks can be roughly divided into three different groups: (i) flow structures, (ii) magmatic enclaves and (iii) physico-chemical disequilibria in melts and crystals (e.g., Walker and Skelhorn 1966; Didier and Barbarin 1991; Hibbard 1995; Flinders and Clemens 1996; Wilcox 1944, 1999; Perugini et al. 2002, 2003; Streck 2008; Perugini and Poli 2012; Morgavi et al. 2016). Flow structures can be readily recognized in field outcrops as they show alternating light and dark coloured bands constituted by magmas with different compositions. Figure 1a, b shows some examples of fluid structures occurring in volcanic rocks from Grizzly Lake outcrop in Yellowstone National Park (USA) (Pritchard et al. 2013; Morgavi et al. 2016) and from Soufrière Hills volcano (Island of Montserrat, UK) (Plail et al. 2014). In particular, Fig. 1a shows flow bands of rhyolitic magma (white) intruding in a basaltic/hybrid magma (red to dark grey) whereas Fig. 1b shows an alternation of flow bands of rhyolitic (white) and hybrid magma (dark grey) across which basaltic enclaves (light grey) occur. The latter are surrounded by flow bands of hybrid filaments (blue).

Magmatic enclaves are probably the structural evidence that, according to common thinking, mostly characterize magma mixing processes. The term magmatic enclave is used to identify a discrete portion of a magma occurring within a host magma with a different composition (e.g., Wilcox 1944; Walker and Skelhorn 1966; Bacon 1986, Didier and Barbarin 1991). Generally, enclaves display quite sharp contacts with the
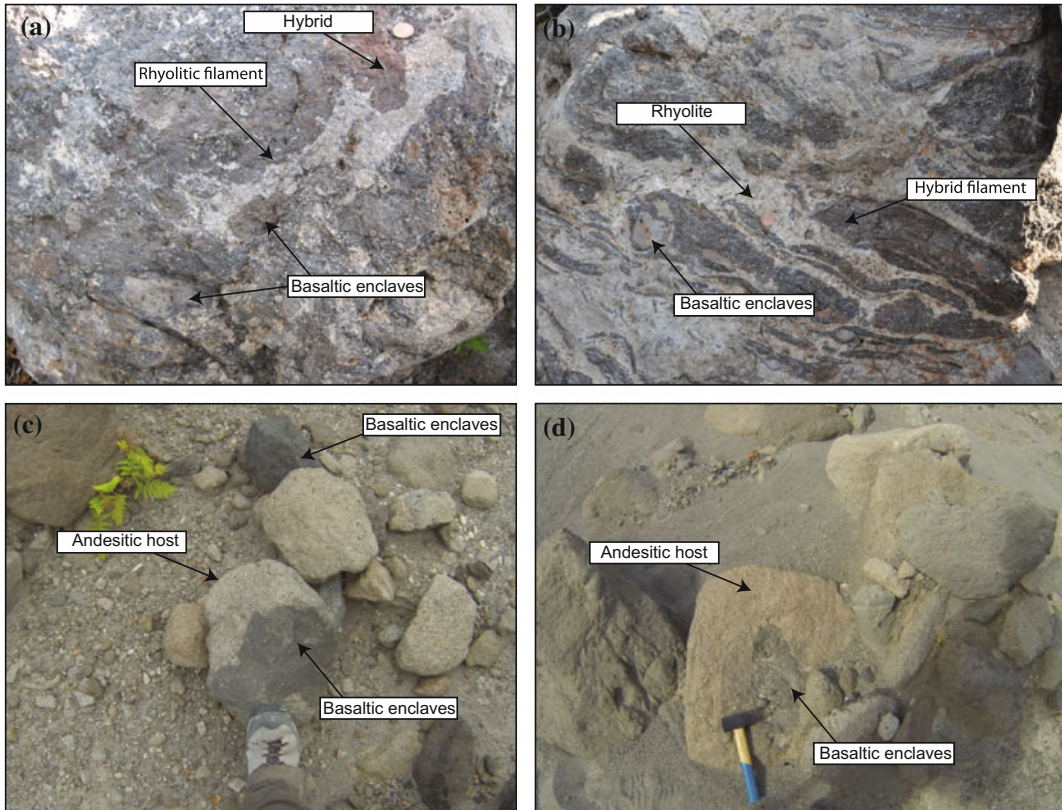
Fig. 1 Detailed images of the mixing features present at Grizzly Lake (Yellowstone) (**a**, **b**) and Soufrière Hills volcano (Montserrat) (**c**, **d**). Figure 1a shows the rhyolitic magma (white) has apparently intruded into the basaltic magma and the hybrid portions are present at the contact between the two end-members. Two large basaltic enclaves are visible at the bottom left and at the centre right. Figure 1b shows the stretching and folding of hybrid magma (dark grey) into a rhyolitic portion (white) with the presence of several basaltic enclaves. Figure 1c shows a basaltic enclave surrounded by andesitic magma (Soufrière Hills, from the 2010 eruption). Figure 1d exhibits at the centre a basaltic enclave in and andesitic host from Soufrière Hills volcano

host rock, although it is not rare to observe that some enclaves display engulfment and disruption of their boundaries due to infiltration of the host magma. Some examples of enclaves found in the volcanic rocks from Soufrière Hills are shown in Fig. 1c, d.

Disequilibrium textures in minerals (Fig. 2a–c) can be viewed as recorders of the thermal and compositional disequilibria operating in the magmatic system during the development of magma mixing processes. As the zoning pattern can be well preserved in minerals from both the plutonic and volcanic rocks, crystal populations from both environments can be used to reconstruct the time evolution of thermal and compositional exchanges between the two magmas during mixing. Recent studies highlighted the importance of detailed investigations of crystal compositional variability not only to reconstruct the fluid-dynamic regime governing the evolution of the igneous body, but also to understand the length-scale of the compositional variability induced by the mixing process, the latter being considered as a proxy to estimate the residence time of magmas in sub-volcanic reservoirs prior to eruption (e.g., Costa and Chakraborty 2004; Martin et al. 2008; Chamberlain et al. 2014; Perugini et al. 2003).
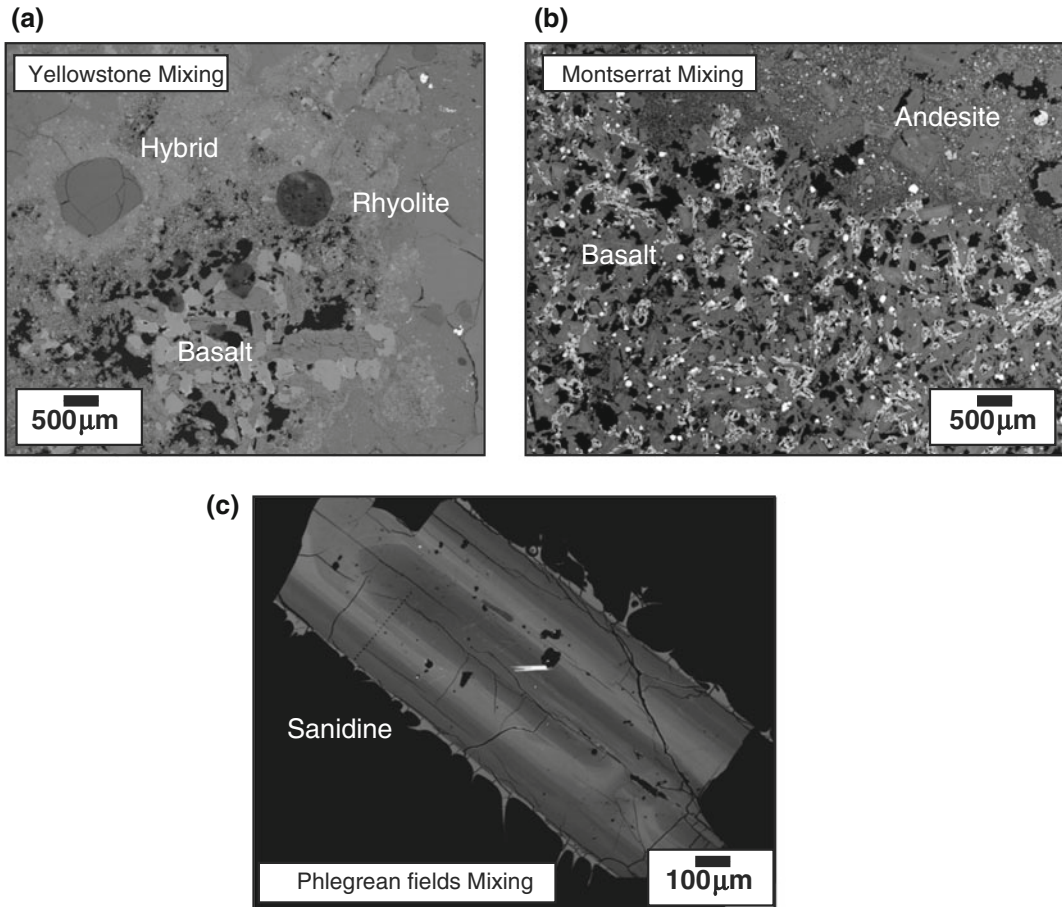
Fig. 2 Backscattered electron (BSE) image of a section of disequilibrium textures in rock and minerals from Yellowstone, Montserrat and Phlegrean Fields. **a** Mixed rock from Grizzly Lake Complex (Yellowstone) showing the interaction between the basaltic portion, the hybrid portion and the rhyolitic portion. **b** Mixed rock section from the 2010 Soufrière Hill eruption (Montserrat) showing disequilibrium texture in the basaltic and the andesitic rock. **c** Crystal from the 4.67 ± 0.09 cal ka Agnano Monte-Spina eruption (Phlegrean fields) occurred from a vent in the Agnano-San Vito area, has a darker (i.e., Ba-poorer) resorbed core and an inner rim with "swirly" zonation textures that indicate crystallization and dissolution. The outer rim is characterized by small-scale wavy oscillatory zoning that results from high-frequency growth and resorption events

3 Numerical and Experimental Studies: New Ideas for Deciphering the Complexity of Magma Mixing

Studies focused on numerical and experimental investigation of magma mixing dynamics (e.g., Perugini et al. 2003, 2008, 2015; De Campos et al. 2004, 2008, 2011; Petrelli et al. 2011; Montagna et al. 2015; Morgavi et al. 2015; Laumonier et al. 2014) can provide additional tools for a better understanding of the complexity of the mixing process, the evolution of which is governed by a continuous exchanges. One of the most striking results arising from these studies is that, during mixing, chemical elements experience a diffusive fractionation process due to the development in time of chaotic mixing dynamics (Perugini et al. 2006, 2008). This process is considered the source of strong deviations in many chemical elements from the linear

variations in inter-elemental plots that would otherwise be expected, based on a conceptual model classically adopted in the geochemical modelling of magma mixing processes (e.g., Fourcade and Allegre 1981; Perugini and Poli 2012 and references therein). Recent studies on the mineralogical and geochemical features of mixed rocks (e.g., Hibbard 1981, 1995; Wallace and Bergantz 2002; Costa and Chakraborty 2004; Perugini and Poli 2005; Slaby et al. 2010), as well as those focused on quantitative analyses of morphologies related to textural heterogeneity (e.g., Wada 1995; De Rosa et al. 2002; Perugini and Poli 2005; Perugini et al. 2002, 2003) have highlighted the dominant role played by chaotic mixing dynamics in producing the substantial complexity of geochemical variations and textural patterns found in the resultant rocks (e.g., Flinders and Clemens 1996; De Campos et al. 2011; Morgavi et al. 2013a, b, c, 2016). Despite significant attention in the past, however, few works have focused on the understanding of the relationship between the morphology of the mixing patterns and the geochemical variability of the system using experimental devices (e.g., De Rosa et al. 2002).

Based upon the combination of field observations and the outcome from numerical simulations, a new experimental apparatus has been developed to perform mixing experiments using high viscosity silicate melts at high temperature (De Campos et al. 2011; Morgavi et al. 2013a, c, 2015). This device has been used to study the mixing process between natural melts, enabling the investigation of the influence of chaotic dynamics on the geochemical evolution of the system of mixing magmas (Morgavi et al. 2013a, b, c, 2015).

Preliminary results indicate that the time evolution of compositional exchanges between magmas from the experiments can be effectively modelled, leading to the prospect that the record of magma mixing processes may serve as chronometers to estimate the time interval between mixing and eruption (Perugini et al. 2010; Perugini and Poli 2012; Morgavi et al. 2013a, b, c, 2015; Perugini et al. 2015).

4 Geochemical Evidence of Magma Mixing/Mingling: An Example from the Campi Flegrei Volcanic Area

In some volcanic areas chemically and isotopically distinct magmas have been erupted, and their composition identified by analyzing the chemical composition of the erupted products (e.g., Pantelleria (Italy), Gedemsa and Fanta 'Ale (Main Ethiopian Rift), Gorely Eruptive Center (Kamchatka); Civetta et al. 1997; Giordano et al. 2014; Seligman et al. 2014). However, in other volcanic complexes the majority of the erupted products are chemically rather homogeneous, displaying a dominant composition (e.g., trachybasalt at Mt. Etna; trachyte at Campi Flegrei, Italy; basalt at Réunion Island, Indian Ocean; andesite at Popocatepetl, Mexico). Despite the roughly homogenous composition of products from these volcanic areas, their isotopic features suggest that complex open system processes occurred and superposed the main fractional crystallization trend. In fact, isotopic analyses (e.g., Sr, Nd, Pd, B) have been proven to be an important tool for discriminating between closed-system fractional crystallization and open-system magma mixing/mingling or crustal contamination (e.g., James 1982; Knesel et al. 1999; Turner and Foden 2001). Combined with petrographic, mineral chemistry and chemical investigations, isotopic analyses on volcanic rocks have revealed compositional variations at different length-scales (bulk rock, minerals, single crystals) pointing to a complex interplay of fractional crystallization, mixing/mingling and crustal contamination during the evolution of several magmatic feeding systems (e.g., Di Renzo et al. 2011 and references therein; Melluso et al. 2012; Corsaro et al. 2013 and references therein; Di Muro et al. 2014 and references therein; Brown et al. 2014). Furthermore, together with conventional isotopic analyses, current technologies permit high precision, in situ determination of Sr isotopic ratios of portions of phenocryst and glasses. In fact, microsampling by MicroMill™, coupled with isotopic measurement by Thermal

Ionization Mass Spectrometry (TIMS), allows for the performance of high precision determination of Sr isotopic composition of single crystals or portions of them. This information, unobtainable from bulk samples, has been used successfully to gather information on the time- and length-scales of the pre-eruptive magmatic processes, for identifying mantle sources and/or magmatic end-members and for tracking the time evolution of magma differentiation (e.g., Davidson et al. 1990; Davidson and Tepley 1997; Davidson et al. 1998; Knesel et al. 1999; Font et al. 2008; Kinman et al. 2009; Francalanci et al. 2012; Braschi et al. 2012; Jolis et al. 2013; Arienzo et al. 2015).

Among the active volcanic areas worldwide the volcanic hazard posed by the Campi Flegrei caldera is extremely high, due to its explosive character. Both the high volcanic hazard and the intense urbanization result in an extreme volcanic risk in this area, leading to a considerable interest in understanding which processes might contribute to triggering of eruptions and controlling? eruptive dynamics. The Campi Flegrei caldera is a nested and resurgent structure in the Campania Region, South Italy (Orsi et al. 1996), possibly formed after two large caldera forming eruptions: the Campanian Ignimbrite eruption (39 ka, Fedele et al. 2008) and the Neapolitan Yellow Tuff (15 ka, Deino et al. 2004). Its magmatic system is still active as testified by the occurrence of the last eruption in 1538 AD, as well as the present widespread fumaroles and hot springs activity, and the persistent state of unrest (Del Gaudio et al. 2010; Chiodini et al. 2003, 2012, 2015; Moretti et al. 2013). For compositionally homogenous magmas such as those extruded at the Campi Flegrei caldera (trachytes and phonolites being by far the most abundant rocks), major oxide and trace element variations cannot be used to unequivocally establish which magma evolution processes operated. Thus, together with petrographic, mineral chemistry and chemical data, isotopic investigations on volcanic rocks spanning the history of the volcano have been performed in recent decades in order to define the role of variable magmatic processes in

the evolution of its feeding system up to eruption (e.g., Civetta et al. 1997; D'Antonio et al. 1999, 2013; de Vita et al. 1999; Pappalardo et al. 2002; Fedele et al. 2008, 2009; Tonarini et al. 2004, 2009; Arienzo et al. 2010, 2011; Perugini et al. 2010; Di Vito et al. 2011; Melluso et al. 2012; Arienzo et al. 2015).

In particular, detailed investigations of the geochemical and isotopic (Sr, Nd, Pb, and B) features of the younger than 15 ka Campi Flegrei volcanic products gave understanding to how many variable magmatic components, rising from large depth and/or stagnating in middle crustal reservoir(s), recharged the shallowest reservoir(s) and interacted with magma batches left from previous eruptions (Di Renzo et al. 2011). One identified magmatic component, geochemically similar to magma from the Neapolitan ca. 0.70750, $^{143}Nd/^{144}Nd$ ratio of ca. 0.51247, $^{206}Pb/^{204}Pb$ of ca. 19.04 and d11B of ca. −7.8‰), has been the most prevalent component over the past 15 ka. A second magmatic component, having geochemical features similar to the Minopoli 2 magma (D'Antonio et al. 1999; Di Renzo et al. 2011), first erupted 10 ka ago, is shoshonitic in composition. It is the most enriched in radiogenic Sr ($^{87}Sr/^{86}Sr$ of ca. 0.70850) and unradiogenic Nd and Pb ($^{143}Nd/^{144}Nd$ ratio of ca. 0.51238, $^{206}Pb/^{204}Pb$ of ca. 18.90), and it is characterised by the lowest d11B value of ca. −7.4‰. The third component is trachytic in composition and is characterized by lower $^{206}Pb/^{204}Pb$ (ca. 19.08), $^{87}Sr/^{86}Sr$ (ca. 0.70720) and d11B (−9.8‰) and higher $^{143}Nd/^{144}Nd$ (ca. 0.51250), with respect to the Neapolitan Yellow Tuff component (Tonarini et al. 2009; Di Renzo et al. 2011; Arienzo et al. 2015). This third composition is known as the Astroni 6 component due to the fact that it best recognized in the Astroni 6 erupted products (Di Renzo et al. 2011). During the past 5 ka of activity, this new component has been suggested to have mixed in variable proportions with the Neapolitan Yellow Tuff and Minopoli 2 magmatic components, which dominated the Campi Flegrei volcanic activity mostly in the time span from 15 to 5 ka (Fig. 3).
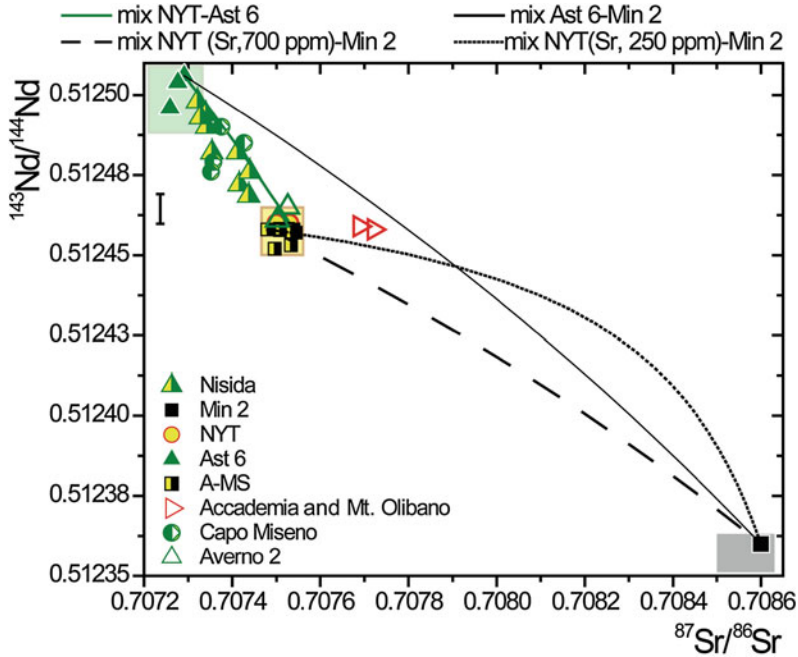
Fig. 3 Modelling of the Sr-Nd isotopic features of some of the Campi Flegrei volcanics of the past 5 ka, by assuming mixing among the Astroni 6 (Ast-6)-, Neapolitan Yellow Tuff (NYT)- and Minopoli 2 (Min 2)-like magmatic components. The green, yellow and black boxes represent the range of Sr and Nd isotopes of the products erupted during the Astroni 6, Neapolitan Yellow Tuff and the Minopoli 2 eruptions, respectively. Symbols inside the plot represent volcanic products belonging to the listed eruptions. The vertical error bar is the uncertainty in 143Nd/144Nd determination at the 2σ level of confidence; that for 87Sr/86Sr is included in the symbols. Modified after Arienzo et al. (2016)

Based on isotope investigations and melt inclusions studies, Arienzo et al. (2016) suggested that the Astroni 6 component, although undergoing differentiation during uprising, had a deep origin (larger than 8 km depth). Indeed, this magma rose not only inside and along the margins of the caldera, but also at the intersection between SE-NW and NE-SW regional fault systems mixing with the NYT-like magma component at shallower depth, and possibly entrapping crystals accumulated during older eruptions.

This detailed study of the Campi Flegrei volcanic system highlights that Sr isotopic micro-analysis and, in general, more conventional isotopic analyses, coupled with petrographic, mineral chemistry and geochemical data can provide a better knowledge of the mixing/mingling processes and of the mixing end-members. In turn, they provide (i) information for evaluating the volcanic hazards and mitigating the related risks and (ii) the basic geochemical and petrologic knowledge for the numerical simulations.

5 Numerical Simulation of Magma Mingling and Mixing

To understand mixing and mingling processes at a realistically large scale, it is necessary to resort to numerical simulations of the complex interaction dynamics between chemically different magmas. Referring to the archetypal case of the Campi Flegrei magmatic system as described above, the interaction of a shoshonite and a more evolved phonolite has been investigated in detail to provide constraints on the time and length scales of the mixing dynamics. The simulated system consists of a very large, deep (8 km) reservoir connected by a dike to a shallower,

Fig. 4 Initial setup for the numerical simulations of magma chamber replenishment at Campi Flegrei caldera. The two interacting magmas are characterized by different compositions and volatile contents, thus densities and gas volume fractions
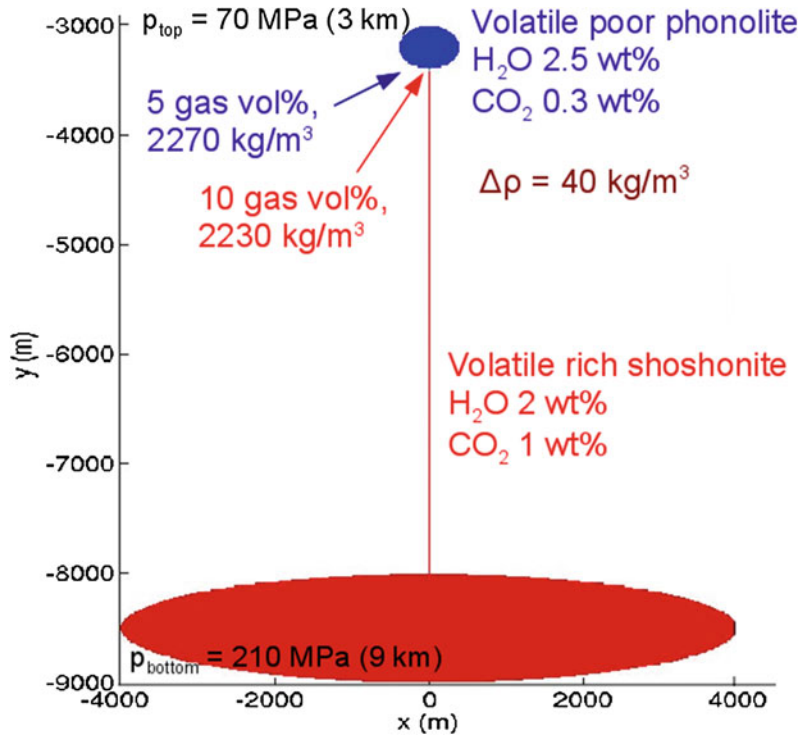
smaller chamber (Fig. 4). The chemical interactions between the two magmas cannot be resolved on the simulated large scale, as the computational costs required would be too high. The shoshonitic magma, being richer in volatiles than the resident phonolitic melt, rises into the phonolitic chamber by buoyancy, generating convection and mixing within the reservoir and in the feeding dike. Both magmatic components include a liquid (silicate melt) and a gaseous phase, that cannot decouple from the host melt. Space-time varying volatile exsolution is computed as a function of local composition, pressure and temperature following Papale et al. (2006). More details on magma chamber dynamics can be found in Chap. 8 'Magma chamber rejuvenation: insights from numerical models' of this book.

The main results show that the chaotic patterns observed in the products and in recently developed experimental setups (Morgavi et al. 2013a, b, c, 2015) are reproducible (Fig. 5), and

that the two magmas mingle very efficiently from the beginning of their interaction. As time progresses, convection slows down due to smaller buoyancy of the incoming mixed component, and the instability proceeds in time asymptotically: the more the two end-members have mingled, the less intense the convection. A time-dependent mixing efficiency η_C can be defined as:

$$\eta_C = \frac{|m_R(t) - m_R(0)|}{m_R(0)}. \tag{1}$$

In the equation above, $m_R(t)$ is the mass of the resident phonolitic magma at time t, thus $m_R(0)$ is the initial phonolite mass. The mixing efficiency η_C represents the relative variation of the mass of the initially resident magma in a certain region of the domain. Figure 6 shows the time evolution of mixing efficiency in the shallow chamber, for different simulated setups in terms of chamber geometry and volatile content. It clearly shows
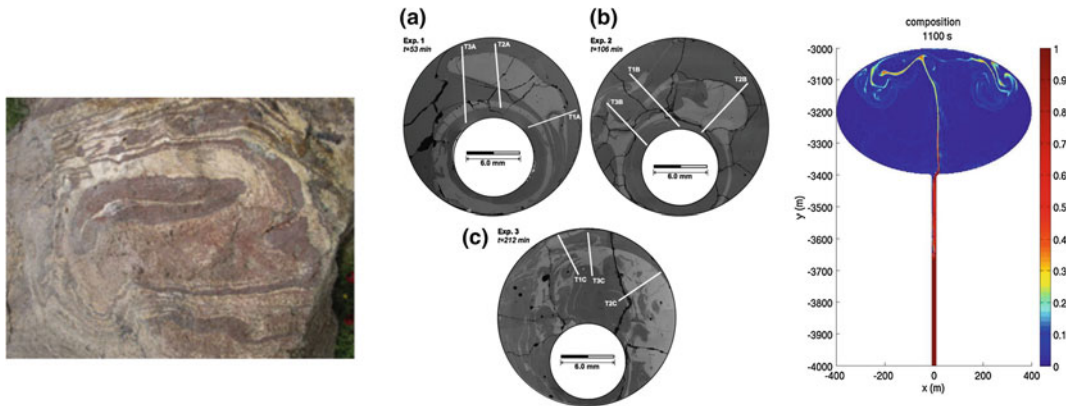
Fig. 5 Magma mixing in natural samples, experimental setups 684 and numerical modelling. Left: Lesvos (Greece) lava flow, from Perugini and Poli (2012); centre: experimental setup, from Morgavi et al. (2013b); right: simulations of magma chamber replenishment

Fig. 6 Variation of convection efficiency with time in the shallow chamber for different simulated scenarios, characterized by varying geometry and total volatile content in the shallow chamber
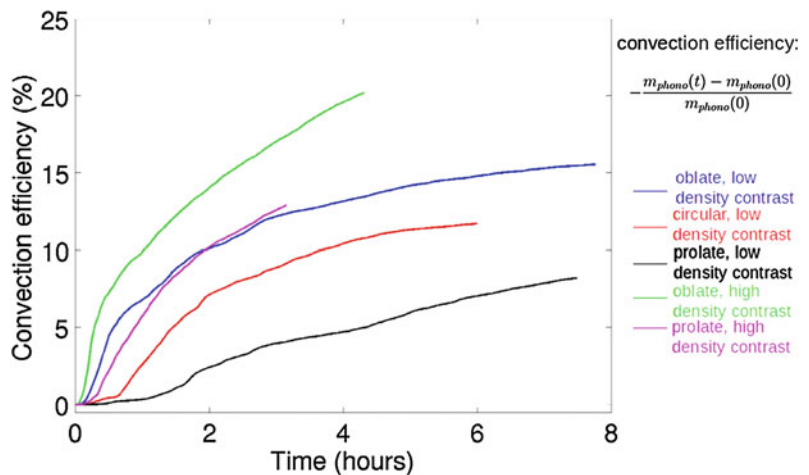
that mingling is very effective on relatively short time scales, on the order of hours, in agreement with mixing timescales derived from the geochemical modelling of magma mixing experiments (Perugini et al. 2010). When buoyancy drives fast dynamics, more than 40% of the original end-member magmas have mingled in the feeder dyke within 4 h from the arrival of the gas-rich magma from depth. The asymptotic behaviour seems to be reached earlier for less efficient setups: after 4–5 h from the onset of the instability, the system seems to have reached a quasi-steady state. In these cases, a much smaller part of the two magmas has mingled.

6 Magma Mixing Time Scale and Eruption Trigger

The most violent and catastrophic volcanic eruptions on Earth have been triggered by the refilling of a felsic volcanic magma chamber by a hottest and more mafic magma (Kent et al. 2010; Murphy 1998). Examples include Vesuvius 79 AD (Cioni et al. 1995), Krakatau 1883 (Self 1992), Pinatubo 1991 (Kress 1997), the Campanian Ignimbrite (Arienzo et al. 2009) and Eyjafjallajökull 2010 (Sigmundsson et al. 2010). Injection of the more mafic magma into the felsic

magma triggers convection dynamics and widespread mixing (Sparks et al. 1977). Vesiculation induced by convection increases magma pressure and may fracture the volcanic edifice triggering an explosive eruption. The injection and mixing process is accompanied by geophysical signals, such as earthquakes, gravity changes and ultra-long-period ground oscillations, that can now be accurately detected (Williams and Rymer 2002; Longo et al. 2012; Bagagli et al. 2017). The knowledge of the time elapsing between the beginning of mixing (and associated geophysical signals) and eruption is thus of greatest importance in forecasting the onset of a volcanic eruption.

Recent studies highlighted that in order to preserve magma mixing structures (i.e., filaments, swirls, bandings) in the rocks, the time elapsed between the beginning of mixing and the subsequent eruption must be very short; on the order of hours or days (Perugini et al. 2010). Preserved structures would indicate mixing was the last process recorded by the magmatic system and its study can unravel unprecedented information on pre-eruptive behaviour of volcanoes.

The compositional heterogeneity produced by magma mixing, and subsequently frozen in time in the volcanic products, can hence be viewed as a broken clock at a crime scene; it can potentially be used to determine the time of the incident. Following this idea and combining numerical simulations with magma mixing experiments using natural compositions and statistical analyses it was shown that for three volcanic eruptions from the Campi Flegrei volcanic system (Astroni, Averno and Agnano Monte Spina) the mixing-to-eruption timescale are of the order of a few minutes (Perugini et al. 2015). These timescales indicate that very little time elapsed from the moment mixing started until eruption. These results are in agreement with recent numerical simulations of magma mixing (Montagna et al. 2015) that highlight mixing timescales of a few hours to attain complete hybridization of magmas for the Campi Flegrei magmatic systems.

These results have implications for civil protection planning of future volcanic crisis as the high velocities of ascending magmas may imply little warning time in volcanic crises. These findings can be a starting point towards a unifying model explaining chemical exchanges in magmatic systems and supplying information on the use of chemical element mobility as geochronometers for volcanic eruptions. This may provide unparalleled clues for building an inventory of past and recent volcanic eruption timescales and could be decisive for hazard assessment in active volcanic areas.

References

Anderson AT (1976) Magma mixing: petrological process and volcanological tool. J Volcanol Geotherm Res 1:3–33

Arienzo I, D'Antonio M, Di Renzo V, Tonarini S, Minolfi G, Orsi G, Carandente A, Belviso P, Civetta L (2015) Isotopic microanalysis sheds light on the magmatic endmembers feeding volcanic eruptions: the Astroni 6 case study (Campi Flegrei, Italy) J Volcanol Geoth Res 304:24–37

Arienzo I, Mazzeo FC, Moretti R, Cavallo A, D'Antonio M (2016) Open-system magma evolution and fluid transfer at Campi Flegrei caldera (Southern Italy) during the past 5 ka as revealed by geochemical and isotopic data: the archetype of Nisida eruption. Chem Geol 427:109–124

Bacon CR (1986) Magmatic inclusions in silicic and intermediate volcanic rocks. J Geophys Res 91:6091–6112

Bagagli M, Montagna CP, Papale P, Longo A (2017) Signature of magmatic processes in strainmeter records at Campi Flegrei (Italy). Geophys Res Lett 44(2):718–725

Baker DR (1990) Chemical Interdiffusion of Dacite and Rhyolite—Anhydrous Measurements at 1 Atm and 10 Kbar, Application of Transition-State Theory, and Diffusion in Zoned Magma Chambers. Contrib Mineral Petr 104:407–423

Bateman R (1995) The interplay between crystallization, replenishment and hybridisation in large felsic magma chambers. Earth Sci Rev 39:91–106

Blundy J, Sparks SRJ (1992) Petrogenesis of mafic enclaves in granitoids of the Adamello massif, Italy. J Petrol 33:1039–1104

Bowen N (1928) The evolution of the igneous rocks. Princeton University Press, Princeton, N.J

Braschi E, Francalanci L, Vougioukalakis GE (2012) Inverse differentiation pathway by multiple mafic magma refilling in the last magmatic activity of Nisyros Volcano, Greece. Bull Volcanol 74:1083–1100

Brown RJ, Civetta L, Arienzo I, D'Antonio M, Moretti R, Orsi G, Tomlinson EL, Albert PG, Menzies MA (2014) Geochemical and isotopic insights into the assembly, evolution and disruption of a magmatic plumbing system before and after a cataclysmic caldera Dcollapse eruption at Ischia volcano (Italy). Contrib Mineral Petrol 168, 1035. doi:https://doi.org/10.1007/s00410-014-1035-1

Bunsen W (1851) Uber die Processe der vulkanischen Gesteinsbildungen Islands. Ann Phys Chem (Dritte Reihe) 83:197–272

Chamberlain KJ, Morgan DJ, Wilson CJN (2014) Time-scales of mixing and mobilisation in the Bishop Tuff magma body: perspectives from diffusion chronometry. Contrib Mineral Petr 167:1034. https://doi.org/10.1007/s00410-014-1034-2

Chiodini G, Caliro S, De Martino P, Avino R, Gherardi F (2012) Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations. Geology 40:943–946

Chiodini G, Todesco M, Caliro S, Del Gaudio C, Macedonio G, Russo M (2003) Magma degassing as a trigger of bradyseismic events; the case of Phlegrean Fields (Italy). Geophys Res Lett 30(8):1434. https://doi.org/10.1029/2002GL01679

Chiodini G, Vandemeulebrouck J, Caliro S, D'Auria L, De Martino P, Mangiacapra A, Petrillo Z (2015) Evidence of thermal-driven processes triggering the 2005–2014 unrest at Campi Flegrei caldera. Earth Planet Sci Lett 414:58–67

Cioni R, Civetta L, Marianelli P, Metrich N, Santacroce R, Sbrana A (1995) Compositional layering and syn-eruptive mixing of a periodically refilled shallow magma chamber: the AD 79 Plinian eruption of Vesuvius. J Petrol 36:739–776

Civetta L, Orsi G, Pappalardo L, Fisher RV, Heiken G, Ort M (1997) Geochemical zoning, mingling, eruptive dynamics and depositional processes—the Campanian Ignimbrite, Campi Flegrei Caldera, Italy. J Volcanol Geotherm Res 75:183–219

Corsaro RA, Di Renzo V, Di Stefano S, Miraglia L, Civetta L (2013) Relationship between magmatic processes in the plumbing system of Mt. Etna and the dynamics of the eastern flank: inferences from the petrologic study of the products erupted from 1995 to 2005. J Volcanol Geotherm Res 251:75–89

Costa F, Chakraborty S (2004) Decadal time gaps between mafic intrusion and silicic eruption obtained by chemical zoning patterns in olivine. Earth Planet Sci Lett 227:517–530

D'Antonio M, Civetta L, Orsi G, Pappalardo L, Piochi M, Carandente A, de Vita S, Di Vito MA, Isaia R (1999) The present state of the magmatic system of the Campi Flegrei caldera based on a reconstruction of its behavior in the past 12 ka. J Volcanol Geotherm Res 91:247–268

D'Antonio M, Tonarini S, Arienzo I, Civetta L, Dallai L, Moretti R, Orsi G, Andria M, Trecalli A (2013) Mantle and crustal processes in the magmatism of the Campania region: inferences from mineralogy, geochemistry, and Sr–Nd–O isotopes of young hybrid volcanics of the Ischia island (South Italy). Contrib Mineral Petr 165:1173–1194. https://doi.org/10.1007/s00410-013-0853-x

Davidson JP, McMillan NJ, Moorbath S, Worner G (1990) The Nevados de Payachata volcanic region (18S, 69 W, N. Chile) II. Evidence for widespread crustal involvement in Andean magmatism. Contrib Mineral Petr 105:412–432

Davidson JP, Tepley FJ III (1997) Recharge in volcanic systems; evidence from isotopic profiles of phenocrysts. Science 275:826–829

Davidson JP, Tepley FJ III, Knesel KM (1998) Crystal isotopic stratigraphy; a method for constraining magma differentiation pathways. Eos 79:185–189

De Campos CP, Dingwell DB, Fehr KT (2004) Decoupled convection cells from mixing experiments with alkaline melts from Phlegrean Fields. Chem Geol 213:227–251

De Campos CP, Dingwell DB, Perugini D, Civetta L, Fehr TK (2008) Heterogeneities in magma chambers: insight from the behaviour of major and minor elements during mixing experiments with natural alkaline melts. Chem Geol 256:131–145

De Campos CP, Perugini D, Ertel-Ingrisch W, Dingwell DB, Poli G (2011) Enhancement of Magma mixing efficiency by Chaotic Dynamics: an experimental study. Contrib Mineral Petr 161:863–881

Deino AL, Orsi G, de Vita S, Piochi M (2004) The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera—Italy) assessed by $^{40}Ar/^{39}Ar$ dating method. J Volcanol Geotherm Res 133:157–170

De Rosa R, Donato P, Ventura G (2002) Fractal analysis of min- gled/mixed magmas: an example from the Upper Pollara eruption (Salina Island, Southern Tyrrhenian Sea, Italy). Lithos 65:299–311

De Rosa R, Mazzuoli R, Ventura G (1996) Relationships between deformation and mixing processes in lava flows: a case study from Salina (Aeolian Islands, Tyrrhenian Sea). Bull Volcanol 58:286–297

de Vita S, Orsi G, Civetta L, Carandente A, D'Antonio M, Deino A, di Cesare T, Di Vito MA, Fisher RV, Isaia R, Marotta E, Necco A, Ort M, Pappalardo L, Piochi M, Southon J (1999) The Agnano-Monte Spina eruption (4100 years BP) in the restless Campi Flegrei caldera (Italy). J Volcanol Geotherm Res 91:269–301

Del Gaudio C, Aquino I, Ricciardi GP, Ricco C, Scandone R (2010) Unrest episodes at Campi Flegrei: a reconstruction of vertical ground movements during 1905–2009. J Volcanol Geotherm Res 195:48–56

Di Muro A, Metrich N, Vergani D, Rosi M, Armienti P, Fourgeroux T, Deloule E, Arienzo I, Civetta L (2014) The shallow plumbing system of Piton de la Fournaise volcano (La Reunion island, Indian Ocean) revealed by the major 2007 caldera forming eruption. J Petrol

55(7):1287–1315. https://doi.org/10.1093/petrology/egu025

Di Renzo V, Arienzo I, Civetta L, D'Antonio M, Tonarini S, Di Vito MA, Orsi G (2011) The magmatic feeding system of the Campi Flegrei caldera: architecture and temporal evolution. Chem Geol 281:227–241

Di Vito MA, Arienzo I, Braia G, Civetta L, D'Antonio M, Orsi G (2011) The Averno 2 fissure eruption: a recent small size explosive event at the Campi Flegrei caldera. Bull Volcanol 73:295–320. https://doi.org/10.1007/s00445-010-0417-0

Didier J, Barbarin B (1991) Enclaves and Granite Petrology, vol 13. Elsevier, Amsterdam

Eichelberger JC (1975) Origin of andesite and dacite: evidence of mixing at Glass Mountain in California and other circum-Pacific volcanoes. Geol Soc Amer Bull 86:1381–1391

Eichelberger JC (1978) Andesitic volcanism and crustal evolution. Nature 275:21–27

Eichelberger JC (1980) Vesiculation of mafic magma during replenishment of silicic magma reservoirs. Nature 288:446–450

Fedele L, Scarpati C, Lanphere M, Melluso L, Morra V, Perrotta A, Ricci G (2008) The Breccia Museo formation, Campi Flegrei, southern Italy: geochronology, chemostratigraphy and relationship with the Campanian Ignimbrite eruption. Bull Volcanol 70:1189–1219

Fedele L, Zanetti A, Morra V, Lustrino M, Melluso L, Vannucci R (2009) Clinopyroxene/liquid trace element partitioning in natural trachyte-trachyphonolite systems: insights from Campi Flegrei (southern Italy). Contrib Mineral Petr 158:337–356. https://doi.org/10.1007/s00410-009-0386-5

Flinders J, Clemens JD (1996) Non-linear dynamics, chaos, complexity and enclaves in granitoid magmas. Trans R Soc Edinburgh: Earth Sci 87:225–232

Font L, Davidson JP, Pearson DG, Nowell GM, Jerram DA, Ottley CJ (2008) Sr and Pb isotopic micro-analysis of plagioclase crystals from Skye lavas: an insight into open-system processes in a flood basalt province. J Petrol 49(8):1449–1471

Fourcade S, Allegre CJ (1981) Trace element behaviour in granite genesis: a case study the calc-alkaline plutonic association from the Querigut Complex (Pyrenees France). Contrib Mineral Petr 76:177–195

Francalanci L, Avanzinelli R, Nardini I, Tiepolo M, Davidson JP, Vannucci R (2012) Crystal recycling in the steady-state system of the active Stromboli volcano: a 2.5-ka story inferred from in situ Sr-isotopic and trace element data. Contrib Mineral Petr 163:109–131

Grasset O, Albarede F (1994) Hybridisation of mingling magmas with different densities. Earth Planet Sci Lett 121:327–332

Hibbard MJ (1981) The magma mixing origin of mantled feldspar. Contrib Mineral Petrol 76:158–170

Hibbard MJ (1995) Petrography to petrogenesis. MacMillan Publishing Company, London

Jolis EM, Freda C, Troll VR, Deegan FM, Blythe LS, McLeod CL, Davidson JP (2013) Experimental simulation of magma-carbonate interaction beneath Mt. Vesuvius, Italy. Contrib Mineral Petr 166:1335–1353

Kent AJR, Darr C, Koleszar AM, Salisbury MJ, Cooper KM (2010) Preferential eruption of andesitic magmas through recharge filtering. Nat Geosci 3:631–636

Kinman WS, Neal CR, Davidson JP, Font L (2009) The dynamics of Kerguelen Plateau magma evolution: new insights from major element, trace element and Sr isotopic microanalysis of plagioclase hosted in Elan Bank basalts. Chem Geol 264:247–265

Knesel KM, Davidson JP, Duffield WA (1999) Evolution of silicic magma through assimilation and subsequent recharge: evidence from Sr isotopics in sanidine phenocrysts Taylor Creek Rhyolites. J Petrol 40:773–786

Kress V (1997) Magma mixing as a source for Pinatubo sulphur. Nature 389:591–593

Lesher CE (1990) Decoupling of chemical and isotopic exchange during magma mixing. Nature 344:235–237

Longo A, Papale P, Vassalli M, Saccorotti G, Montagna CP, Cassioli A, Giudice S, Boschi E (2012) Magma convection and mixing dynamics as a source of Ultra-Long-Period oscillations. Bull Volcanol 74(4):873–880. doi:https://doi.org/10.1007/s00445-011-0570-0, https://doi.org/10.1007/s00445-011

Martin VM, Morgan DJ, Jerram DA, Caddick MJ, Prior DJ, Davidson JP (2008) Bang! Month-scale eruption triggering at Santorini Volcano. Science 321:1178

Melluso L, De' Gennaro R, Fedele L, Franciosi L, Morra V (2012) Evidence of crystallization in residual, Cl-F-rich, agpaitic, trachyphonolitic magmas and primitive Mg-rich basalt-trachyphonolite interaction in the lava domes of the Phlegrean Fields (Italy). Geol Mag 149(3):532–550

Montagna CP, Papale P, Longo A (2015) Timescales of mingling in shallow magmatic reservoir. In: Caricchi L, Blundy JD (eds) Chemical, Physical and Temporal Evolution of Volcanic Systems. Gelogical Society, London, Special Publications 422, pp 131–140

Morgavi D, Perugini D, De Campos CP, Ertl-Ingrisch W, Dingwell DB (2013a) Time evolution of chemical exchanges during mixing of rhyolitic and basaltic melts. Contrib Mineral Petr 166(2):615–638

Morgavi D, Perugini D, De Campos CP, Ertl-Ingrisch W, Dingwell DB (2013b) Morphochemistry of patterns produced by mixing of rhyolitic and basaltic melts. J Volcanol Geotherm Res 253:87–96

Morgavi D, Perugini D, De Campos CP, Ertl-Ingrisch W, Lavallee Y, Morgan L, Dingwell DB (2013c) Interactions Between Rhyolitic and Basaltic Melts Unraveled by Chaotic Magma Mixing Experiments. Chem Geol 346:119–212

Morgavi D, Petrelli M, Vetere FP, Gonzalez-Gartia D, Perugini D (2015) High temperature apparatus for chaotic mixing of natural silicate melts. Rev Sci Instrum 86(10):105108

Morgavi D, Arzilli F, Pritchard C, Perugini D, Mancini L, Larson P, Dingwell BD (2016) The Grizzly Lake complex (Yellowstone Volcano, USA): mixing between basalt and rhyolite unraveled by microanalysis and X-ray microtomography. Lithos 260:457–474

Murphy MD (1998) The role of Magma Mixing in triggering the current eruption at the Soufriere Hills Volcano, Montserrat, West Indies. Geophys Res Lett 25:3433–3436

Laumonier M, Scaillet B, Pichavant M, Champallier R, Andujar J, Arbaret L (2014) On the conditions of magma mixing and its bearing on andesite production in the crust. Nature communications, volume 5

Papale P, Moretti R, Barbato D (2006) The compositional dependence of the saturation surface of $H_2O + CO_2$ fluids in silicate melts. Chem Geol 229(1–3):78–95

Pappalardo L, Piochi M, D'Antonio M, Civetta L, Petrini R (2002) Evidence for multistage magmatic evolution during the past 60 kyr at Campi Flegrei (Italy) deduced from Sr, Nd and Pb isotopic data. J Petrol 43(8):1415–1434

Perugini D, De Campos CP, Dingwell DB, Petrelli M, Poli G (2008) Trace element mobility during magma mixing: preliminary experimental results. Chem Geol 256:146–157

Perugini D, de Campos CP, Petrelli M, Dingwell DB (2015) Concentration variance decay during magma mixing: a volcanic chronometer. Sci Rep 5:14225

Perugini D, Petrelli M, Poli G (2006) Diffusive fractionation of trace elements by chaotic mixing of magmas. Earth Planet Sci Lett 243:669–680

Perugini D, Petrelli M, Poli G, De Campos C, Dingwell DB (2010) Time-scales of recent Phlegrean fields eruptions inferred from the application of a 'Diffusive Fractionation' model of trace elements. Bull Volcanol 72:431–447

Perugini D, Poli G (2005) Viscous fingering during replenishment of felsic magma chambers by continuous inputs of mafic magmas: field evidence and fluid-mechanics experiments. Geology 33:5–8

Perugini D, Poli G (2012) The mixing of magmas in plutonic and volcanic environments: analogies and differences. Lithos. https://doi.org/10.1016/j.lithos.2012.02.002

Perugini D, Poli G, Gatta G (2002) Analysis and simulation of Magma mixing processes in 3D. Lithos 65:313–330

Perugini D, Poli G, Mazzuoli R (2003) Chaotic advection, fractals and diffusion during mixing of Magmas: evidence from Lava Flows. J Volcanol Geotherm Res 124:255–279

Perugini D, Valentini L, Poli G (2007) Insights into Magma chamber processes from the analysis of size distribution of Enclaves in Lava Flows: a case study from Vulcano Island (Southern Italy). J Volcanol Geotherm Res 166:193–203

Petrelli M, Perugini D, Poli G (2011) Transition to Chaos and implications for Time-scales of Magma Hybridization during mixing processes in Magma chambers. Lithos 125:211–220

Plail M, Barclay J, Humphreys MCS, Edmonds M, Herd RA, Christopher TE (2014) Characterization of mafic enclaves in the erupterd products of Soufriere Hills Volcano, Montserrat, 2009–2010. In Wadge G, Robertson REA, Voight B, (eds) The eruption of Soufriere Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, Memoirs, 39, 343–360

Poli G, Tommasini S, Halliday AN (1996) Trace elements and isotopic exchange during acid-basic magma interaction processes. Trans Royal Soc Edinburgh: Earth Sci 87:225–232

Pritchard CJ, Larson PB, Spell TL, Tarbert KD (2013a) Eruption-triggered mixing of extra-caldera basalt and rhyolite complexes along the East Gallatin-Washburn fault zone, Yellowstone National Park, WY, USA. Lithos 175–176:163–177. doi:https://doi.org/10.1016/j.lithos.2013.04.022

Self S (1992) Krakatau revisited: the course of events and interpretation of the 1883 eruption. Geoj Lib 28:109–121

Sigmundsson F, Hreinsdottir S, Hooper A, Arnadottir T, Pedersen R, Roberts JM, Oskarsson N, Auriac A, Decriem J, Einarsson P, Geirsson H, Hensch M, Ofeigsson BG, Sturkell E, Sveinbjornsson H, Feigl LK (2010) Intrusion triggering of the 2010 Eyjafjallajokull explosive eruption. Nature 468:426–430

Slaby E, Gotze J, Worner G, Simon K, Wrzalik R, Smigielski M (2010) K-feldspar phenocrysts in microgranular magmatic enclaves: a cathodoluminescence and geochemical study of crystal growth as a marker of magma mingling dynamics. Lithos 105:85–97

Smith JV (2000) Structures on interfaces of mingled magmas, Stewart Island, New Zealand. J Struct Geol 22:123–133

Sparks SRJ, Marshall LA (1986) Thermal and mechanical constraints on mixing between mafic and silicic magmas. J Volcanol Geotherm Res 29:99–124

SparksSRJ Sigurdsson H, Wilson L (1977) Magma mixing: a mechanism for triggering acid explosive eruptions. Nature 267:315–318

Tonarini S, D'Antonio M, Di Vito MA, Orsi G, Carandente A (2009) Geochemical and isotopical (B, Sr, Nd) evidence for mixing and mingling processes in the magmatic system feeding the Astroni volcano (4.1–3.8 ka) within the Campi Flegrei caldera (South Italy). Lithos 107:135–151

Tonarini S, Leeman WP, Civetta L, D'Antonio M, Ferrara G, Necco A (2004) B/Nb and 5^{11}B systematics in the Phlegrean Volcanic District (PVD). J Volcanol Geotherm Res 113:123–139

Ventura G (1998) Kinematic significance of mingling-rolling structures in lava flows: a case study from Porri volcano (Salina Southern Tyrrhenian Sea). Bull Volcanol 59:394–403

Wada K (1995) Fractal structure of heterogeneous ejecta from the Meakan volcano, eastern Hokkaido, Japan: implications for mixing mechanism in a volcanic conduit. J Volcanol Geotherm Res 66:69–79

Walker GPL, Skelhorn RR (1966) Some associations of acid and basic igneous rocks. Earth Sci Rev 2:9–109

Wallace G, Bergantz G (2002) Wavelet-based correlation (WBC) of crystal populations and magma mixing. Earth Planet Sci Lett 202:133–145

Wiebe RA (1994) Silicic magma chambers as traps for basaltic magmas: the Cadillac mountain intrusive complex, Mount Desert island, Maine. J Geol 102:423–427

Wilcox RE (1944) Rhyolite-basalt complex of Gardiner River, Yellowstone Park, Wyoming. Geol Soc Am Bull 55:047–1080

Wilcox RE (1999) The idea of Magma Mixing: history of a struggle for Acceptance. J Geol 107(4):421–432

Williams-Jones G, Rymer H (2002) Detecting volcanic eruption precursos: a new method using gravity and deformation measurements. J Volcanol Geotherm Res 113:379–389