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Diego Perugini

The Mixing of Magmas

Field Evidence, Numerical Models, Experiments

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To my wife Laura, who was brave enough to believe in the impossible.

To my son Lorenzo. In the vortexes of chaos, it's a privilege for me to travel next to your trajectory.

To Giulia, who will never be a physicist. Listen to your heart and follow your dreams.

To my parents, Umbra and Nello.

Preface

We adore chaos because we love to produce order.

M. C. Escher

Since the beginning of what we call today Science, researchers have attempted to describe and understand Nature by building models. However, the scientific practice is characterized by a great diversity. It assumes different forms in different disciplines, in different historical periods, according to research schools and individual scientists. To date, a unitary model has not yet been devised accounting for the scientific practice in all its variety and complexity. Until such a model will exist, the best way to describe and understand Nature is to develop partial models, each accounting reasonably for its various aspects. This is what has also happened in the branch of petrology that deals with the process of magma mixing. Although there is a vast literature on this subject, most of the works are focused on the study of particular cases and the results are rarely used for general and unitary interpretations. This may be due to various causes and, among these, probably the most relevant one is that magma mixing can occur in a large number of forms, very variable from case to case, which can be complex to include in a single general conceptual framework. Although, therefore, it may appear legitimate to study this natural process using partial models, the most serious risk is to create a scientific field that is separate from the other disciplines, which could not only benefit from the results of this type of research, but, above all, may provide fundamental indications for a better understanding of the process itself. I refer first of all to those scientific disciplines, such as physics and mathematics, which are often referred to as "exact sciences", and therefore considered barely useful in the study of Nature in which precision and reproducibility are rare qualities. But there is also another risk. A compartmentalized study inevitably causes the marginalization of the importance of a natural process that risks to be considered as a deviation of a natural system, which, therefore, represents the exception rather than the rule. If at the beginning the process attracts the attention of researchers, it is inevitably destined to be relegated to the "geological zoo of bizarre cases" and sooner or later it will be forgotten. This happens because, although that particular case belongs to a much wider class of processes having a single common thread, it lacks in fact of a general fundamental theory that supports it coherently. The main issue is therefore to make efforts in order to generalize the results from the studies carried out on magma mixing with the aim of constructing a common basis to the different occurrences. A possible approach to this problem may come from the application of theories and techniques that allowed to establish universal characters in many scientific fields: Chaos Theory and Fractal Geometry. This is what I attempted to do in the last twenty-five years of research on igneous systems. During the course of my scientific activity, I explored different aspects of magma mixing using different tools borrowed from the fields of mathematics and physics, together with conventional petrological and volcanological tools. Unfortunately, the COVID-19 emergency almost stopped our research activity and I had the opportunity to have time to look back and realize that this might be the right time to put together the work we had done so far in a more organized way. In doing this I realized two things. The first is that we did a huge amount of work in order to understand the multifaceted nature of magma mixing combining field work, numerical models, and high-temperature experiments. The second is that we are still far from having a coherent conceptual framework accounting for the complexity of this natural process. Nevertheless, I feel that petrologists and volcanologists might appreciate leafing through this little book. I wish to warn the reader that, although this book reports several natural case studies, numerical models and results from experiments, it will not go too much through the mathematical details. The interested readers will find their way to deepen these technical aspects in other sources, including the cited references. On the contrary, this book is mostly intended to stimulate new ideas in students, young and possibly more experienced researches to move further steps to understand what I believe is one of the most important petrological and volcanological processes: the mixing of magmas.

Colle Umberto I, Perugia, Italy Diego Perugini
May 2021

Acknowledgements

I wanted to be a paleontologist and I ended up an igneous petrologist. The responsible for this is Giampiero Poli, my master and Ph.D. supervisor, and most of all a good friend. I still remember the day I stepped into his office asking about a master project on granitoid rocks from Northern Greece. Needless to say, my interest was mostly on “retsina” than on granites at that time. A few weeks later it was time to fly to Thessaloniki and I went back to Giampiero’s office to have some clarifications about fieldwork. He drew a mysterious black blob on a recycled sheet of paper and said: “you have to collect these things in the granitoid masses of the Sithonia Plutonic Complex”. I must confess that when I went to Giampiero’s office I was a little bit confused. After I left, I was still confused, but on another level. A few days later, I was in the field with George Christofides and George Eleftheriadis and I realized that those black blobs were mafic microgranular enclaves. This was my very first encounter with the extraordinary world of magma mixing. Thank you Giampiero, I would have been a terrible paleontologist and, most of all, I would have missed about twenty years of fabulous research activity we carried out together. This was the time when I learned to do Science.

Roughly in the same period of time another scientist influenced my scientific life: Angelo Peccerillo. The unforgettable discussions with Angelo about geochemical modeling and geodynamics had for me a priceless value.

Around 2000, while I was desperately trying to finish my Ph.D. work, a timid guy knocked to the door of the “Ph.D. student cave”. His name is Maurizio Petrelli and he asked for information about a master project on building stones. Lost in my thoughts, I handed him a book on artificial intelligence, asking him to start studying the subject. A week later he showed up with a bunch of working programming scripts. I still have the pleasure to work with Maurizio. Thank you for being what you are: a pragmatic scientist and a friend.

2004 represented a tipping point in my scientific career. This was the year when Jörn Kruhl organized the Fourth International Conference on Fractals and Dynamic Systems in Geoscience. Here I had the opportunity to meet Benoit Mandelbrot and Don Turcotte. Sometimes even a few words pronounced by an eminent scientist can change your mind fueling your interests toward amazing directions. Thank you Jörn, Benoit and Don!

It was during this conference that I also met Kai-Uwe Hess. He invited me to visit the laboratories of Don Dingwell in Munich. I did so and everything changed. Here, I had the privilege to meet Don, Werner Ertel-Ingrisch, Cristina de Campos and Ulrich Küppers (Ulli). We started a wonderful collaboration that culminated with my stay in Munich for one year as a Humboldt Fellow. In this time, we built the first prototype of chaotic magma mixing device. I still remember our excitement while running the very first experiment. Thank you guys, our scientific meetings at the Oktoberfest were crucial!

A few years later I had the honor to receive a Consolidator Grant from European Research Council Executive Agency. This allowed me to build a new high-temperature lab in Perugia and to organize a wonderful research group. I was lucky enough to recruit excellent researchers, Daniele Morgavi, Maurizio Petrelli and Francesco Vetere, who I wish to thank deeply for their enthusiasm and skills they offered to this adventure.

I am deeply indebted with the Ph.D. students that I had the pleasure to supervise in these years and that shared their time with me in the lab and fieldwork. Among them: Diego González-García, Stefano Rossi, Rebecca Astbury, Kathrin Leager, Joali Paredes Mariño, Alessandro Pisello and Matteo Bisolfati.

I wish also to express all my gratitude to Sandro Conticelli. Although I know he would say “I didn’t do anything”, we both know that he rescued my scientific life at least twice. Thank you, Sandro.

I also thank all the colleagues who in these years were kind enough to listen to my discussions about magma mixing, chaos and fractals and for making me aware, as vice-director of Department of Physics and Geology of the University of Perugia, of the limits of my patience.

Last, but definitely not least, I wish to thank my wife Laura for giving me the opportunity to refuge in our chicken-coop, which we transformed into a little office for smart-working during the COVID-19 pandemic. She inspired this book and, although she will probably never read it because she is a geomorphologist, her role was decisive.

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Part II Numerical and Experimental Simulation of Magma Mixing

Part III Magma Mixing: A Petrological Process

Part I

General Overview

1 What is Magma Mixing?

No Geologist worth anything is permanently bound to a desk or laboratory, but the charming notion that true science can only be based on unbiased observation of nature in the raw is mythology. Creative work, in geology and anywhere else, is interaction and synthesis: half-baked ideas from a bar room, rocks in the field, chains of thought from lonely walks, numbers squeezed from rocks in a laboratory, numbers from a calculator riveted to a desk, fancy equipment usually malfunctioning on expensive ships, cheap equipment in the human cranium, arguments before a road cut.

Stephen. J. Gould, "An Urchin in the Storm"

Abstract

This introductory chapter provides a broad overview of magma mixing processes in the volcanic and plutonic environments. The structural, textural and geochemical evidence for magma mixing is briefly discussed, with the aim to provide a general picture about this fundamental, yet relatively poorly known, natural phenomenon. The arguments presented in this chapter will be discussed in greater detail in the next chapters.

1.1 Historical Perspective

Scientific hypotheses generally cross through different stages. The first one is the observation of a new occurrence which is regarded significant, as it differs or contradicts the conventional view about a specific natural phenomenon. The second stage is based on measurements and modelling to quantify, reproduce, and understand the new phenomenon. We can say, therefore, that the infancy of a hypothesis is mostly characterized by observation, whereas its maturity is based on quantification. Infancy and maturity are connected by an intermediate stage in which we realize that observation is not enough to understand satisfactorily the phenomenon and, thus, we need to move to more evolved stages.

In 1851, the chemist Bunsen (1851) published a work suggesting that mixing of magmas might originate most of the compositional variability observed in igneous rocks. Several petrologists criticized ferociously this work and the magma mixing idea was rejected for almost one century (see e.g. Wilcox 1999 for a historical overview). The rise of fractional crystallization as the new paradigm for magma differentiation (Bowen 1915) contributed to bury the magma mixing idea. Nevertheless, around the 1950s the magma mixing idea reinvigorated as the result of the unequivocal indications documented in the rocks (e.g. Bailey and McCallien 1957; Wager and Bailey 1953). After an infancy of about twenty five years, in which a number of observations accumulated (e.g.

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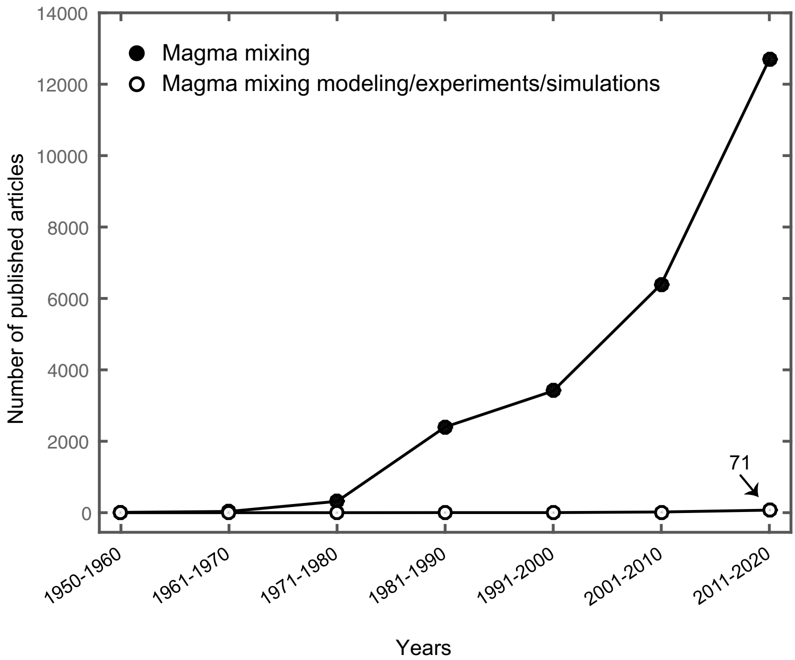

Fig. 1.1 Plot showing the number of papers published on magma mixing from 1950 to 2020. For each ten-year period, the expressions "magma mixing", "magma mixing modelling/experiments/simulations" were used to query the database. *Source data* Google Scholar, January 2021

Walker and Skelhorn 1966; Yoder 1973), this process moved to an intermediate stage (e.g. Huppert et al. 1980; Kouchi and Sunagawa 1985; Oldenburg et al. 1989; Sparks and Marshall 1986; Turner and Campbell 1986; Vernon et al. 1988) and progressively evolved towards maturity (e.g. Bergantz 2000; Jellinek and Kerr 1999; Petrelli et al. 2011, 2018). Figure 1.1, shows the number of articles published on the subject in the time interval 1950–2020. For each ten-year period, the sentences "magma mixing", "magma mixing modelling/experiments/simulations" were used to query the Google Scholar database. The plot displays that starting from 1980s the number of works containing "magma mixing" increases exponentially up to a value of approximately 13000 in 2010–2020. Contrarily, the number of articles containing "modelling, experiments or simulations" remains close to zero up to the beginning of 1990s and, then, it grows very slowly, indicating that the maturity stage may still take time to be reached.

Many works suggest that the magma mixing is a key process in controlling the compositional variation in igneous rocks (e.g. Blundy and Sparks 1992; De Campos et al. 2004; Wiebe 1994) and triggering volcanic explosions (e.g. Leonard et al. 2002; Murphy et al. 1998). However, despite the recognized importance of this process in both igneous petrology and volcanology, and the progresses in experimental and numerical modelling strategies (e.g. Perchuk 1993; De Campos et al. 2011; Laumonier et al. 2014; Perugini et al. 2003; Zimanowski et al. 2004), we are still far from a satisfactory understanding of the physical-chemical mechanisms of magma mixing.

1.2 What Is Magma Mixing?

It has become common practice to apply the term "magma mingling" to refer to the process of physical dispersion (no chemical exchanges are involved) of one or more magmas in another magma. The term "magma mixing" is instead used to indicate that mingling is also accompanied by chemical exchanges (e.g. Flinders and Clemens 1996). Regrettably, such a jargon is rarely used in the literature generating misunderstandings. Although it is often not easy to distinguish between the two processes, we support the idea that pure mingling is not a common process in Nature. As