

## ROLE OF FLUIDS IN IGNEOUS PETROGENESIS

**Maria Luce Frezzotti**

*University of Siena, Italy*

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### Contents

1. Introduction
  2. Magmatic Fluids
    - 2.1. Definition of Magmatic Volatiles
    - 2.2. Solubility of Magmatic Volatiles in Silicate Melts
    - 2.3. Composition of Exsolved Fluids
  3. Remnants of Magmatic Fluids in Igneous Rocks: Melt and Fluid Inclusions in Minerals
  4. Origin of Magmatic Fluids: Earth Degassing and Recycling
  5. Modeling Magmatic Fluids
    - 5.1 Fluids and Genesis of Basaltic Magma in the Mantle
    - 5.2. Fluids and Origin of Granitic Melts in the Crust
    - 5.3. Role of H<sub>2</sub>O in Fractional Crystallization Processes
  6. Influence of Magmatic Fluids on Geological Phenomena
    - 6.1 Explosive Volcanism
    - 6.2. Volcanic, Hydrothermal Systems and Geothermal Reservoirs
- Glossary  
Bibliography  
Biographical Sketch

### Summary

Magmatic volatiles, chiefly H<sub>2</sub>O and CO<sub>2</sub>, are present dissolved in magmas at high pressures. Such volatiles may exist as immiscible fluid phases at low-pressure conditions or after partial crystallization of the melt (volatile oversaturation).

Magmatic volatiles can originate in different ways, directly from degassing of the mantle or by recycling of surface waters. In igneous petrogenesis, fluids are important to determine the melting conditions of mantle and crustal rocks, and as a consequence, the pressure, time and chemical conditions of formation of most basaltic and rhyolitic magmas. As magma cools down, volatile phases may influence the type of minerals that may crystallize, and at the final crystallization stages they may form pegmatitic rocks.

Exsolution of volatiles from magma is associated with several significant geological processes. Explosive volcanism is driven, in most cases, by volatile exsolution from the silicate melt and because of the enormous increase of fluid volume, following

immiscibility. Fluid exsolution in magma bodies cooling at depths may cause circulation of hydrothermal solutions and form ore deposits.

## 1. Introduction

The formation of igneous rocks is the culmination of a sequence of events initiated by prograde heating of the protolith and followed by formation of a grain-boundary melt, melt segregation into a vein network, ascent of the melt through the network, and finally, crystallization of the melt (intrusive igneous rocks) or eruption to the Earth's surface (effusive igneous rocks). The amount of melt generated during partial melting processes of rocks in the crust and in Earth's mantle depends on several factors, among which are the fertility of the source rock (that is, how close the composition of the protolith is to a minimum eutectic composition), pressure and time (P–T) conditions, and the availability of fluids. During partial melting processes occurring in closed systems, fluids and in particular water seem to be provided by decomposition of hydrous phase like micas or amphibole. However, if the proportions of hydrous phases are low or P–T conditions are not adequate for their breakdown, the influence of another factor like the input of an external fluid phase channeled through anatectic contacts can be decisive in the generation of melts.

Volatiles also play a major role in forcing the rise of the newly generated magmas towards the Earth's surface. Many volatile phases can be dissolved in a molten silicate; since their solubility increases with pressures, the ascent of magmas to the surface with a consequent decrease in confining pressures causes them to come out as a solution to form bubbles (magmatic immiscibility or boiling processes). Therefore, the study of volatile elements may provide information about the role of fluids in igneous petrogenesis, and thus of volatiles in partial melting processes and during the overall evolution of magmas.

In this article, I will review the chemical-physical characteristics of volatile phases in igneous rocks and provide information on the role that they actively play in igneous petrogenesis.

## 2. Magmatic Fluids

What takes place in the Lipari isles affords an additional proof that the winds circulates underneath the earth.

Aristotle

More than 2000 years ago the Greeks moved to the Aeolian Islands and had the opportunities to see volcanic eruptions. The “wind” made of air and gases released during volcanic eruptions was at the basis of the theory that involved Aeolus, a giant imprisoned in a cave beneath the islands and known as the master of the winds. More recently, but as early as the eighteenth century, the French geologist Dolomieu recognized that pumice was gas-bubble-bearing obsidian (volcanic glass). The British scientist Scrope was the first to recognize that the expansive force of “elastic aeriform fluids” (magmatic fluids) could provide the energy necessary for magmatic eruption.

Although the concept that magmas contained gases was introduced so early, it was only from the second half of the nineteenth century that the major role of fluids in igneous petrogenesis was recognized, and it took more than a century to introduce experimental studies on silicate melt systems and on natural rocks.

## 2.1. Definition of Magmatic Volatiles

That magmas contain large amount of volatile species is evident from many processes such as volcanic explosions, like the one of Mt. St. Helens in Washington State, U.S.A. in 1980, or of Soufrière, Montserrat, in 1992–1993. The emission of volcanic gases is also associated with fumaroles in midoceanic ridges, oceanic island hot spot volcanoes, and stratovolcanoes over subduction zones. However, magmas during crystallization and/or cooling may lose a large part of their volatile components, and igneous rocks often retain only a limited record of the original amount of fluids dissolved. An indirect way of modeling magmatic fluid is represented by laboratory experiments. Experimental studies, in fact, allow the modeling of the composition of magmatic volatiles and evaluation of their effect on phase relationships (see *P–T–Pf Conditions of Metamorphism*).

Many different gases form what we define as “magmatic fluids.” Such gases are named as *volatile components* for their tendency to form immiscible separate phases, at near atmospheric pressures and high magma temperatures. Most magmatic volatiles consist of only six low-atomic-weight elements: H, C, O, S, Cl, and F. Water (H<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) are by far the most abundant fluid species in the Earth and are therefore constituents of magmatic volatiles. Other important volatile components are represented by SO<sub>2</sub>, CO, H<sub>2</sub>S, H<sub>2</sub>, S, and O<sub>2</sub>. HCl, HF, F, N<sub>2</sub>, NH<sub>3</sub>, and noble gases (that is, He and Ar) represent minor constituents. Sulfur is particularly important for understanding the composition and fluxing of volcanic gases during eruptions and the genesis of many ore deposits. The behavior of halogens is complex, since if water is present very high salinity aqueous fluids are formed (that is, brines, hydrosaline melts) which play a major role in forming magmatic-hydrothermal ore deposits. Noble gases, although present only in small concentrations (in parts per million—ppm, 0.1 wt%) are of interest since their isotopic study allows one to understand the large-scale degassing of Earth and the formation of Earth’s asthenosphere (see *Applications of Isotopes to Igneous Petrogenesis*).

For volatile species, as the confining pressure of the system increases, dissolved molecules of gas are forced together until the “critical point” is reached. Above this point (at 371.4 °C and 218 bars for water, and 31.1 °C and 73 bars for carbon dioxide) gaseous and liquid phases are no longer distinguishable: they are called “fluid phases.” At a depth of 1 km or more, therefore, water and carbon dioxide exist as fluid phases, or simply fluids. The densities of such fluids are high, and can be up to 1 g cm<sup>-3</sup>, similar to that of surface water in lake or stream.

In shallow volcanic systems, at depth of a few km and magmatic temperatures, the densities of such fluids are very low and < 0.1 g cm<sup>-3</sup>, and the term “gas” (or “vapor” for H<sub>2</sub>O) is more appropriate.

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### Biographical Sketch

**Maria Luce Frezzotti** was born in December 1961. She graduated in Geology *cum laude* at the University of Siena in 1984. In 1990 she obtained her Ph.D. in Petrology. From 1990 to 1993 she worked as a postdoctoral researcher at the Vrije Universiteit in Amsterdam, the Netherlands. From 1993, she was a researcher in petrology at the University of Siena., where is presently serving as Deputy Professor of Volcanology. Since 1998 she has been in charge of a “Socrates” European Union program for university teaching in the member states.

Her main scientific interests include the petrology of fluid phases, igneous petrology, volcanology, and metamorphic petrology. Fluid–rock interaction processes in igneous and metamorphic rocks through the study of fluid and melt inclusions have been and are still her main research topics. She is the author or co-author of some 34 scientific papers published in international journals, and editor of two books.

Maria Luce Frezzotti is Associate Editor of the *European Journal of Mineralogy*. At present, she acts as an expert for the Geological and Environmental Sciences at the European Union in Brussels.