IGNEOUS AND METAMORPHIC PETROLOGY

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Summary

Magmatic rocks are produced by the cooling of magmas. These are formed in the continental crust and in the upper mantle by partial melting (or anatexis) of rocks. Their chemical composition depends on the composition of parent rock, the degree of partial melting, and the nature of the minerals that enter into the melt. Magmas have lower density than the parent rocks, and after their formation they separate from the source

and migrate toward the surface. Magmas can cool inside the earth or can erupt at the surface, giving intrusive and extrusive rocks. During their cooling inside the earth, minerals crystallize slowly and separate from magmas. Magmas can melt and incorporate wall rocks, or can mix with other magmas. All these processes, known as "differentiation" or "evolution" processes, cause strong variations in the original composition of magmas.

Metamorphism is a process occurring beneath the Earth's surface, and consists in the structural and mineralogical modification of rocks when they are subjected to high pressure and temperatures. The temperatures of metamorphic processes range from the upper limit of diagenesis (about 150 to 200 °C) to the lower limit of magmatism (about 700 to 800 °C). Pressure is higher than about 0.1 GPa. Metamorphic reactions occur in the solid state and do not produce extensive modification of the bulk chemical composition of the rocks. In some cases, however, rocks can experience strong modification of their chemical composition. This process is called "metasomatism," and is one of the processes responsible for the accumulation of many mineral deposits of economic interest.

Metamorphism and magmatism have been acting continuously in the Earth's system and are responsible for the present structure and composition of the planet. Therefore, understanding metamorphic and magmatic processes has an important bearing on issues of global interest, including the birth and evolution of life on Earth.

1. Introduction

The Earth's crust and mantle are essentially made up of magmatic and metamorphic rocks. Therefore, studies of magmatic and metamorphic processes are crucial for the aim of understanding the genesis and evolution of our planet. The cooling of magmas forms igneous or magmatic rocks. Magmas are very hot, liquid materials that are formed inside the Earth by the partial melting or *anatexis* of rocks. Most magma has a silicate composition, with the exception of the rare *carbonatites* that basically consist of carbonates. Magmas contain gaseous substances in solution, and very often crystals in suspension. In some cases, gas can separate from the liquid magma to form a free gaseous phase. Such a process is more likely to occur at low pressure (that is, near to the surface) because the solubility of gases in magmas decreases with decreasing pressure.

Metamorphic rocks are formed by textural and mineralogical modifications to igneous and sedimentary rocks when these are subjected to high pressure and temperature. Metamorphic rocks themselves may also undergo metamorphism. These types of rocks are called *polymetamorphic*. The temperature at which metamorphism takes place ranges from about 150 to 200 °C, to about 700 to 800 °C. Temperatures below this range are typical of *diagenesis*, whereas those higher than the upper limit mark the beginning of anatexis, with a transition to ultrametamorphism and magmatism (see *Ultrametamorphism and Crustal Anatexis*). Therefore metamorphic temperatures lie in between diagenesis and magmatism, and metamorphic reactions occur in the solid state. The pressure at which metamorphism occurs ranges from about 0.1 GPa to more than 1 GPa. These correspond to depths of 2 to 3 km to several tens of km inside the earth.

Since average geothermal earth gradient is about 30 °C km^{-1}, it can be deduced easily that most of the rocks forming the crust and mantle are indeed metamorphic.

In this review, I will briefly recall the main physical and chemical characteristics of magmas and will summarize their genetic, evolution, and cooling processes. The second part of this article will be dedicated to metamorphic and metasomatic processes. Finally, the relations between petrogenesis and geodynamic processes, and the role of magmatism in the genesis of continents and stabilization of climate on earth, will be discussed briefly.

2. The Magmatic Process

2.1. Chemical Composition of Magmas

The chemical composition of magmas can be estimated by analyzing igneous rocks. Chemical data obtained on a large number of samples reveal that oxygen is the most abundant element and represents about 50% by weight (wt%) of the total mass of magmas. Si, Al, Fe, Mg, Ca, Na, K, Ti, and P occur at concentration levels ranging from about 0.5 to 1wt% to more than 25 to 30 wt% and are known as "major elements." Because of the predominance of oxygen, the composition of magmas and of magmatic rocks is conventionally expressed as weight percent of the oxides of major elements. In silicate igneous rocks, silica (SiO_2) is the most abundant major oxide, followed by Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5.

The abundance of silica is used to classify magmas and igneous rocks into *ultrabasic* ($SiO_2 < 46$ wt%), *basic* ($SiO_2 = 46$-52 wt%), *intermediate* ($SiO_2 = 52$-63 wt%), and *acid* ($SiO_2 > 63$ wt%). Major oxides do not vary randomly but display regular trends when plotted against silica. Fe_2O_3, FeO, MgO, CaO, and TiO_2 are more abundant in basic than in acid magmas. Alkalis have an opposite trend. P_2O_5 generally increases with increasing silica in the basic–intermediate magmas, but drops to low values in acid magmas. It will be shown that these trends depend on the nature of the processes that have a leading role in the differentiation of magmas. Magmas also contain all the other elements of the periodic table. However, their concentrations are very low, at the level of parts per million or ppm (1 ppm = 1mg kg^{-1}) or parts per billion or ppb (1ppb = 1mg tonne^{-1}) or even lower. These diluted elements are known as "trace elements" (see *Behavior of Trace Elements in Magma Genesis and Evolution*).

An additional important compositional parameter of magmas and igneous rocks is given by their isotopic composition, that is, by the relative abundance of different isotopes of some elements (see *Applications of Isotopes to Igneous Petrogenesis*). This is generally expressed as ratios of different isotopes of single elements, or as the deviation of the isotope ratio of the sample from that of a reference standard. Isotope ratios of great use in igneous petrology include: $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{18}O/^{16}O$.

The Na_2O+K_2O to SiO_2 relationship is used to classify magmas into *subalkaline*, *alkaline*, and *transitional* groups. Each group is characterized by variable silica abundances, but less variable alkali contents, which increase from subalkaline to alkaline magmas (Figure 1). Subalkaline magmas are divided into *tholeiitic* and *calcalkaline*, the latter being more enriched in alkalis, especially K_2O. Both transitional and alkaline magmas can be subdivided into K-transitional (or *shoshonitic*) and Na-transitional, and into K-alkaline and Na-alkaline. Na-transitional and Na-alkaline magmas have Na_2O/K_2O ratios higher than unity. K-transitional and K-alkaline magmas have Na_2O/K_2O ratios lower than unity.
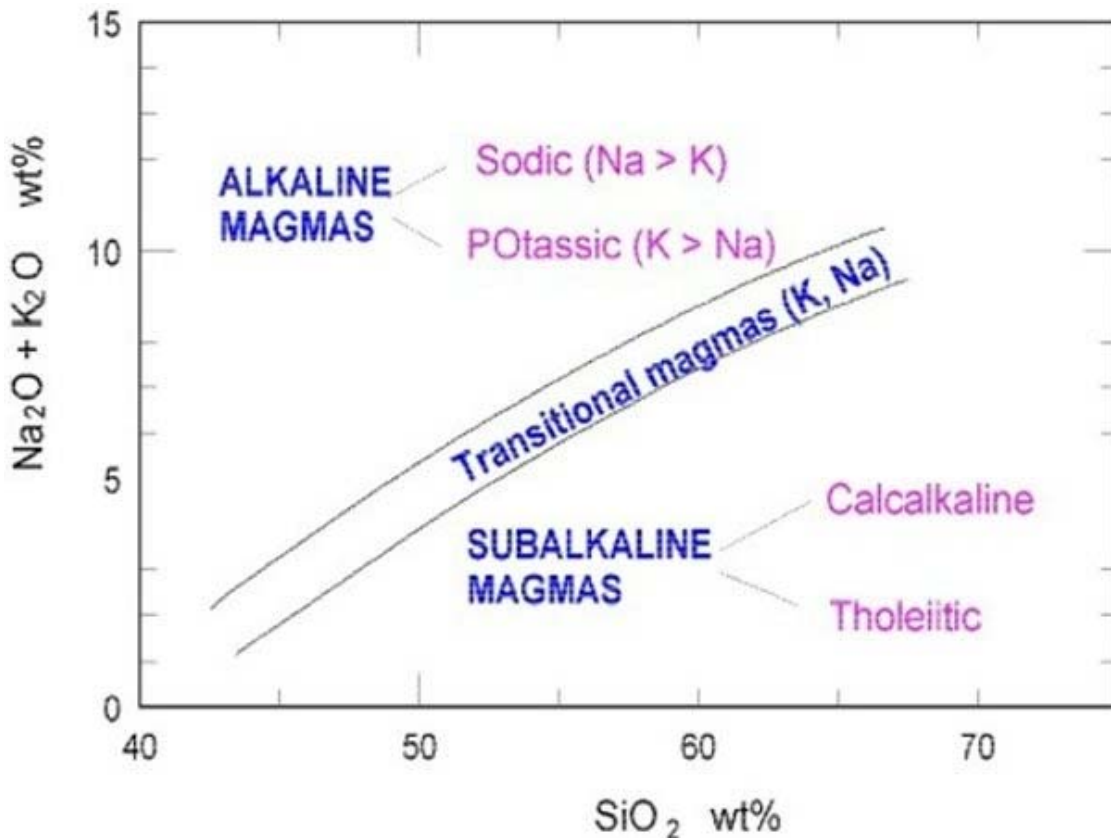

Figure 1. Diagram showing Na_2O+K_2O vs. SiO_2 compositional fields of subalkaline, transitional and alkaline magmas and magmatic rocks

The composition of gaseous components in magmas can be determined by analyses of gases emitted from fumaroles of dormant volcanoes or released during volcanic eruptions, and by analyzing fluid inclusions trapped within minerals and glasses of igneous rocks (see *Role of Fluids in Igneous Petrogenesis*). This last technique has developed enormously in the last few years, and has been able to furnish a huge amount of information on the composition of gases associated with various types of magma. The available data indicate that H_2O and CO_2 are the most abundant volatile species, followed by F, Cl, and various compounds of sulfur (for example, SO_2, SO_3). Water is highly soluble in the magmas at moderate and high pressure, whereas CO_2 is soluble only at high pressure (> 1–2 GPa).

A particular way of indicating the composition of magmas and of igneous rocks is using "normative mineralogy." This is calculated from the chemical composition of rocks, on a volatile-free basis, that is, excluding volatiles. The normative mineralogy is an equilibrium theoretical mineralogical composition; in other words the normative composition represents the mineralogical composition that a rock would have if the magma crystallized very slowly, in equilibrium conditions. Normative minerals may be present or may not be present in the real rocks, depending on how much the cooling history of the magma departs from equilibrium crystallization. In general terms, if magmas cool slowly (that is, in intrusive bodies), crystallization conditions are close to equilibrium and the normative mineralogy may match very closely the real mineralogical composition of the rocks ("modal mineralogy"). On the other hand, if magmas cool rapidly, the resulting rock has a mineralogy that may be very different from the normative composition. Normative mineralogy furnishes important information, especially on the saturation conditions of various components in the magmas. For instance, rocks containing normative quartz denote magma oversaturated in silica; rocks containing normative feldspathoids (for instance, nepheline or leucite) indicate undersaturation in silica; rocks that do not contain either quartz or feldspathoids are saturated in silica.

2.2. Physical Properties of Magmas

The most important physical properties of magmas are temperature, viscosity, and density. Temperature varies from about 750 °C to about 1250 °C, and increases from basic to acid magmas. *Liquidus* and *solidus* temperatures characterize magmas. Liquidus temperatures are those above which magmas become completely melted; solidus temperatures are those of complete solidification. Naturally occurring magmas generally have temperatures between their respective solidus and liquidus. In a few cases, however, magmas may have temperature higher than their liquidus: these are called *superheated* magmas. Magmas that have temperatures between their liquidus and solidus consist of a liquid phase containing various amounts and types of minerals; the quantity of crystals occurring in these magmas increases as the magma temperature approaches the solidus .

The viscosity of magmas depends on their chemical composition. Acid liquids may have viscosity as high as 10^7 to 10^8 Pa s; basic liquids may have viscosity around 10^3 to 10^4 Pa s. Carbonatitic liquids are even more fluid.

Density also depends on the chemical composition. Basic magmas have a density around 2500 to 2600 kg m^{-3} at ambient pressure, whereas acid magmas have a density around 2000 kg m^{-3}. The lower density of acid magmas is because they have a lower concentration of heavy cations such as Fe, Ti, and Ca than basic magmas. The density of magmas increases with pressure. For instance, basic magmas have a density of about 2800 kg m^{-3} at upper mantle pressures. The presence of dissolved volatile components produce a decrease in density; accordingly, degassed magmas have a higher density than gas-rich ones, at constant major element composition and pressure.

2.3. Factors Controlling the Composition of Magmas

All known magmas are formed either in the upper mantle or in the lower or intermediate continental crust (see *Melting in the Mantle; Ultrametamorphism and Crustal Anatexis*). Magmas generally have a lower density than their parent rocks, which causes the magmas to segregate and rise toward the surface. Magmas can be erupted at the surface or can cool inside the Earth to form "volcanic" and "intrusive" rocks, respectively. It is estimated that the large majority of magmas formed inside the Earth cools at depth, whereas only 15 to 20 percent is erupted at the surface. During their way to the surface, magmas generally undergo a complex series of processes that modify their original composition. These processes go under the general name of *magmatic differentiation* or *evolution*. Unmodified magmas are called *primary*, whereas those that have undergone evolution processes are called *evolved* or *derivative*. Accordingly, two main stages can be recognized in the magmatic process: i) *generation of magmas* within the source by partial melting of rocks; ii) *differentiation of magmas* during their ascent to the surface.

As stated earlier, major elements, trace elements, and isotopic ratios are the most important compositional parameters of magmas. These parameters depend on different factors, which behave independently during magma genesis and differentiation.

2.3.1. Major Element Composition

The major element composition of primary magmas depends on the composition and relative amounts of the minerals entering into the liquid phase during partial melting. In other words, the primary magmas have the same major element composition as the minerals that participate in the partial melting. For instance, magmas that contain abundant MgO, FeO, and CaO and a moderate or low content of Na_2O and K_2O (for example, tholeiitic basalts) can be only formed by melting of various amounts of phases, such as olivine and pyroxene, which contain Ca, Fe, and Mg, and are depleted in alkalis. Instead potassic alkaline basalts, which contain high MgO, FeO, and CaO, but also high K_2O up to 6 to 8 wt%, can be formed by the melting of olivine and pyroxene, plus a phase rich in potassium, such as phlogopite.

Petrological phase diagrams can be used to understand from a quantitative viewpoint the close relationships between the major element composition of magmas, and the nature and amounts of mineral phases going into the melt. Figure 2 is the forsterite (Mg-olivine, Mg_2SiO_4)-diopside ($CaMgSi_2O_6$)-silica (SiO_2) phase diagram at high pressure. Forsterite, diopside, and enstatite are the main components of *peridotite*, the rock forming the upper mantle. Therefore, the subtriangle forsterite–diopside–enstatite is important to understand melting processes within the upper mantle; a star indicates average mantle composition. If a peridotite consisting forsterite + diopside + enstatite undergoes partial melting at upper mantle pressure in hydrous conditions, the major element composition of the early-formed melt plots at point P (minimum melting point). With ongoing melting, the composition of the magma remains constant at P, until one or more of the three phases melts completely. In other words, the major element magma composition is "independent of the degree of partial melting," until at least one of the phases melts completely. When a phase disappears (it first occurs for clinopyroxene), the liquid composition changes along the line P–C, becoming richer in forsterite and

enstatite components. Experimental petrology data show that the position of the minimum melting point changes as a function of pressure and of the nature of the fluid phase present in the system. P' is the position of the minimum melting point at 2 GPa in dry conditions (Figure 2). This means that the amount of phases that participate in the melt is different in the two cases; accordingly, the magmas formed in dry conditions are different (that is, are richer in the forsterite component) from those formed in hydrated conditions; these are closer to the silica apex (that is, are richer in silica), and lie in the triangle en–di–silica (that is, are oversaturated in silica).

Obviously, natural processes are more complex than those described by simplified phase diagrams such as that shown in Figure 2. In fact, the mantle does not consist only of pyroxene and olivine but also contains accessory phases such as phlogopite and amphibole, which are not represented in the simplified phase diagram of Figure 2. The presence of these minerals modifies significantly the phase diagrams of mantle systems. However, in spite of this and other complications (for example, minerals that change in composition during melting), the principle remains valid that the major element composition of magmas is a function of the relative amounts and compositions of phases that participate in the melting. As mentioned earlier, if phlogopite is present in the mantle, its melting generates a magma rich in potassium.
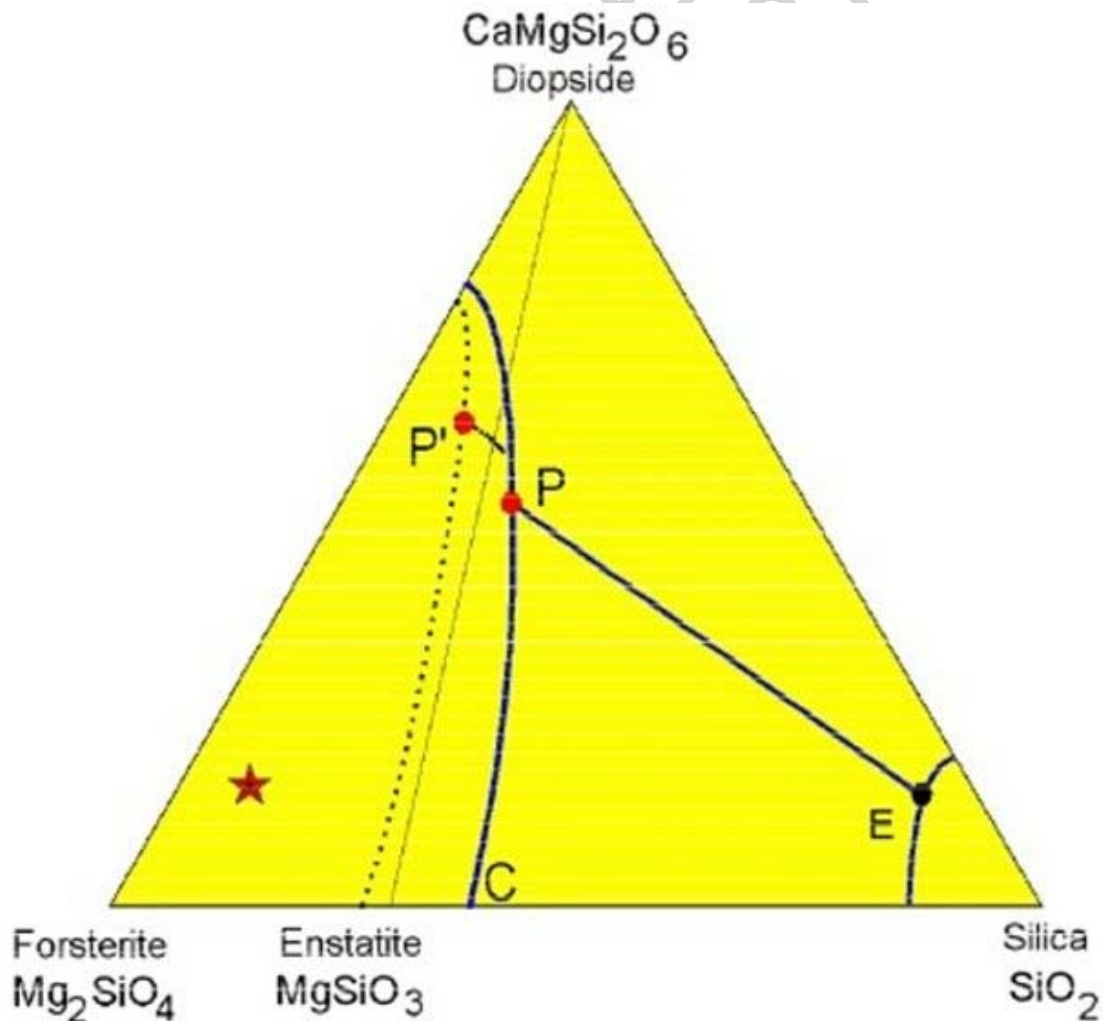
Figure 2. Phase diagram forsterite–diopside–silica at high pressure (1.5–2.0 GPa). Point P represents the composition of the first batch of melt formed by anatexis of a hydrated peridotite. Note that the position of point P moves to P' in dry conditions.

2.3.2. Trace Elements Composition

Trace elements behave differently from major elements during magmatic processes. The equation that describes the variation of trace elements during equilibrium partial melting (see *Behavior of Trace Elements in Magma Genesis and Evolution*) is:

$$C_l/C_0 = 1/(D(1-F)+F) \tag{1}$$

where C_l is the concentration of a given trace element in the magma; C_0 is the concentration of the same element in the source rock; F is the degree of partial melting; D (also indicates as K_{bulk}) is the bulk partition coefficient, that is, the concentration ratio of the element between the bulk residual solid and the coexisting liquid (C_{solid}/C_{melt}). D is calculated from partition coefficients "K" of single minerals, which are determined experimentally. F ranges from zero (no liquid present) to one (complete melting).

Some elements such as Th, U, Ta, Nb, light rare earth elements (LREE), and Zr, generally have a tendency to partition strongly into the liquid phase rather than in the main magmatic minerals (i.e., $D \approx 0$). These elements are known as *incompatible*, in contrast with *compatible elements*, which are readily hosted by igneous minerals and are more abundant in the solid than in the melt (that is, $D > 1$) . For incompatible elements Eq. (1) becomes:

$$C_l/C_0 \approx 1/F \tag{2}$$

Eqs. (1) and (2) clearly show that the concentration of any element in the magma depends on the concentration of the element in the source rock, the degree of partial melting, and the partition coefficients of the phases that are "left in the residue" after partial melting. These factors are different from those affecting major elements. Therefore, the information that can be obtained from the study of trace elements is different from that arising from major elements.

Studies of trace elements give information of paramount interest on the genesis of magmas. They are useful to understand source composition and the degree of partial melting. For example, mantle-derived magmas have concentrations of incompatible elements that vary over several orders of magnitude. Some elements such as U, Th, and Ta occur at a concentration level of a few ppm or ppb in tholeiitic basalts, whereas they reach concentrations of several tens of ppm in potassic alkaline basalts. The implication is that alkaline basalts are formed by much lower degrees of partial melting than tholeiitic basalts. Moreover, incompatible element ratios are independent of the degree of partial melting, and primitive magmas inherit these values from parent rocks. Incompatible trace element ratios of the upper mantle depend heavily on its evolution history (that is, metasomatic modification, and so on). Therefore, incompatible element ratios of basaltic magmas are important for understanding mantle processes.

2.3.3. Isotopic Composition

The interest of igneous petrologists in isotopic ratios (for example, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$) arises from the fact that magmas inherit the isotope signatures of their sources, if equilibrium conditions occur during melting. The isotopic compositions of rocks within the earth are variable (see *Applications of Isotopes to Igneous Petrogenesis*). Therefore, the isotope signatures of magmas can furnish important information on the nature of their source rocks. For instance, the upper mantle has average present-day $^{87}Sr/^{87}Sr$ ratios around 0.704. The continental crust has much higher and more variable Sr isotope values. Primitive mantle-derived basaltic magmas preserve Sr isotope ratios of the upper mantle source. However, if the Sr isotopic signature of a particular basalt is higher than mantle values, the conclusion must be drawn that this basaltic magma has undergone interaction with crustal rocks. Alternatively, it can be envisaged that this particular basalt has been formed by melting of an anomalous mantle, that is, of a mantle that has undergone metasomatic modification (see *Melting in the Mantle*).

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Biographical Sketch

Angelo Peccerillo graduated in Geology *cum laude* at the University of Florence in 1970. From 1971 to 1982 he was Assistant Professor of Petrology, and from 1982 to 1985 he was Associate Professor of Volcanology at the Faculty of Sciences of the University of Florence. In 1985 he become Full Professor of Petrology and in such a position he has run courses at the University of Messina, University of Calabria, University of Addis Ababa, and University of Perugia, where he is presently serving as Full Professor of Petrology and Deputy Professor of Volcanology.

His main scientific interests include igneous petrology, volcanology, geochemistry, the chemistry of igneous minerals, tectonics, subduction-related intrusive and extrusive magmatism, ultrapotassic magmatism, continental rift volcanism, and geochemical modeling of the plumbing system of active volcanoes, and these have been and are still his main research topics. He is author or coauthor of some 130 scientific papers mostly published in peer-reviewed international journals, two books and of several didactic and popular scientific publications.

Angelo Peccerillo has acted as Guest Editor of several special issues of well-known Italian and international journals, such as *Lithos, Chemical Geology* and *Periodico di Mineralogia*. He has been also associate editor of the *European Journal of Mineralogy* and *Acta Vulcanologica.* At present, he is a member of the Editorial Board of the international journal *Lithos* and *Journal of Volcanology and Geothermal Research.*

Angelo Peccerillo is a member of several Italian and international scientific associations, such as Società Italiana di Mineralogia e Petrologia, IAVCEI, and AGU.

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