VOLCANIC AND MAGMATIC ROCKS

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Keywords: Magma, lava, petrology, magmatism, plutonism, volcanism, classification, igneous rocks, plutonic, dyke and volcanic rocks, pyroclastic rocks, structure and texture of rocks, volcanology, landforms of volcanic products, intrusive and extrusive (effusive) products, utilization of rocks, zeolites

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Summary

The Earth‘s internal regime is associated with heat derived from the radioactivity of U, Th, and K, and from the early thermal history of the planet. This internal heat causes plate motions, earthquakes, orogenic movements, and volcanic activity on the surface of the Earth. Localized heat and pressure in the mantle and lower crust causes melting of

materials and formation of magma. Magmas intrude into higher levels of the crust or extrude on the Earth‘s surface as lava. The structure, texture, and form of magmatic bodies reflect physico-chemical, chemical, and mechanical conditions of magma cooling. Magma differentiation is a result of fractional crystallization, partial melting, liquid immiscibility, mixing of magmas, and so on. After cooling, magma may form a wide range of igneous rocks of different compositions from basic to intermediate and acid in composition (based on SiO_2 content). The principal series of igneous rocks include alkaline and subalkaline rock series formed by calc-alkaline and tholeiitic suites (based on SiO_2 vs. total alkali content ratio). Volcanic products, often including xenoliths from the deep part of the crust or mantle, can serve as a window upon the Earth's interior. Volcanic activity occurs in different styles and forms, principally near convergent and divergent lithospheric plate boundaries and also within the plates.

1. State of the Art

Petrography is a branch of geology dealing with the description, microscopic characteristics, and classification of rocks, including igneous rocks. Petrology is a younger discipline of geology that deals with the nature, occurrence, and crystallization of rocks. Petrography developed as an independent subject at the end of the eighteenth century when igneous, metamorphic, and sedimentary rocks were recognized. Volcanology is a branch of geology which studies recent volcanic activity, is able to forecast volcanic events, and applies actualistic principles to the characteristics of ancient rocks to determine their origin, the paleoenvironment, and types of older volcanic activity. The fundamental problem of igneous petrology concerns the nature and origin of igneous rocks. The igneous origin of lavas and volcaniclastic material produced by numerous recent active volcanoes has long been known and recognized; however, a magmatic origin for the most widespread igneous rocks such as granite, gabbro, or even basalt and rhyolite was not generally accepted until recently. Two unforgiving scientific schools of neptunists headed by A.G. Werner, and plutonists headed by J. Hutton, explained the origin of these rocks in different ways. Plutonists associated the origin of such rocks, including dyke rocks, with precipitation from an aquatic milieu. Plutonists preferred a deep igneous origin of the above mentioned rocks. Even the king of poets and scientist, J.W. Goethe, was involved in this broad debate and actively helped, perhaps against his inclination, the total victory of plutonistic ideas. H.C. Sorby, F. Zirkel, and H. Rosenbusch greatly shifted progress in geological recognition through the common application of the microscope in petrography.

Three substantial processes were considered to be important for the diversification of magma: differentiation, assimilation, and mixing. Crystallization was identified by N.L. Bowen as a principal process in diversification of igneous rocks in the first third of the twentieth century, and the importance of partial melting of the mantle and crust was recognized by P.J. Wyllie in the last third of the century. However, the most important shift in the interpretation of the origin of igneous rocks was associated with the application of the plate tectonic concept in the 1960s (H. Hess, J.T. Wilson) based on A. Wegener's theory of continental drift.

2. Origin of Igneous Rocks

Almost all geology is ultimately related to the internal heat of the Earth—the internal engine driving plate motion, earthquakes, orogeny, and volcanism. The internal heat is derived from the radioactivity of U, Th, and K, together with relict heat from the time of the birth of the Earth and the differentiation of the planet. The majority of the internal heat reaches the surface by convective flow from the mantle; its surface manifestation is the process of sea-floor spreading. In continental conditions, the highest values of heat flows are concentrated in (sub)recent rifts and orogenic belts.

Magma is the original material from which all igneous rocks come. It is a natural, very hot melt, originated beneath the surface of the Earth and made up largely by solutions of silicates, oxides, sulphides, and sometimes of carbonates. Magma formed deep within the Earth contains appreciable amounts of the so-called volatile components (see below). The temperatures of magma range from 500 to 1200 ^{o}C. Magma can be formed in any arbitrary part of the Earth where the temperature reaches the parameters necessary for rocks to melt. However, the magmas we know from geological experience generally originate at two depth ranges of the Earth. Basaltic basic magmas originate in the upper mantle as a consequence of melting of lherzolite (olivine, orthopyroxene, clinopyroxene ± garnet, spinel, plagioclase) or the modelled rock pyrolite (basalt and peridotite in a 1: 3 ratio).

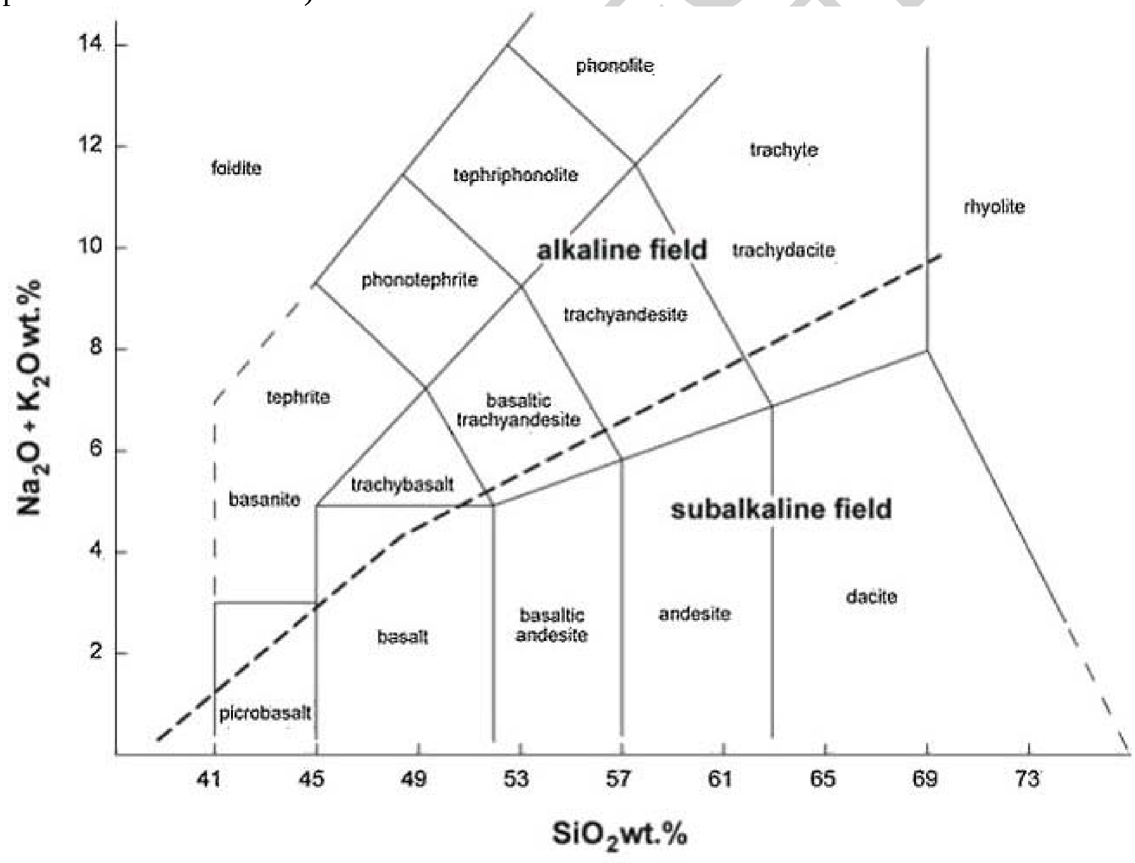

Figure 1. Chemical classification and nomenclature of volcanic rocks using the total alkali versus silica (TAS) diagram (IUGS classification; Le Maitre ed. 1989; simplified). Discrimination line of alkali and subalkali rock fields after Irvine and Baragar (1971).

Magmatism is a common designation for all processes associated with the generation of magma and development of igneous (magmatic) rocks, irrespective of the place where the processes take place (either (a) under the Earth's surface, or (b) on the Earth's surface). Processes associated with the emplacement and cooling of magma in the depths of the Earth are known under the name plutonism. Processes associated with the ascent of magma on the surface are usually included under the term "volcanism." In areas of fractured or weakened lithosphere, the magma rises, squeezed up by the weight of the overlying crust, where it erupts as lava. In recent decades, an active role for the magmatic process (mantle plume theory) has received more and more consideration.

Magma originated by partial melting of either mantle material (basaltic types of magma) or crust material (granitic types of magma). Its primary variation is due to:

- the character of materials being melted in the magmatic source
- the degree of melting
- the conditions of melting.

Secondary variation of the magma depends on the following processes:

- magmatic differentiation
- contamination (assimilation by melting, assimilation without melting)
- zone melting
- magma mixing.

The evolution of different igneous rocks from a common parental magma is called magmatic differentiation. Magmatic differentiation causes changes in the primary homogeneous magma composition. The following mechanisms of differentiation are usually recognized:

- crystal fractionation (gravitational settling, flow differentiation, filter pressing, selective nucleation, gas streaming, gravitational liquid separation). Accumulation of crystals that settle out from magma by gravitational settling is called cumulate (accumulative rock)
- liquid immiscibility (silicate vs. silicate, phosphate, carbonate, sulphide melts)
- liquid fractionation (thermal diffusion, gravitational diffusion)

Magmatic processes involve both plutonic (deep, abyssal) processes associated with the formation of magma and volcanic (superficial and shallow subsurface) processes associated with the deposition of igneous products. We distinguish the different products of magmatic processes according to the conditions (depths) in which the magma cooled. Rocks formed from deep-seated masses of magma solidifying deeply beneath the surface in the crust are called intrusive, while rocks solidifying above the surface, such as volcanic lava, are called extrusive or effusive. Similarly, bodies of igneous rocks are also called intrusive and extrusive (see section 3).

On the basis of tectonic setting, four different environments of magma generation are distinguished:

1. constructive plate margins—divergent plate boundaries (mid-oceanic ridges and back-arc spreading centres) → tholeiitic magma series (mostly basalts)
2. destructive plate margins—convergent plate boundaries (island arcs and active continental margins) → tholeiitic, calc-alkaline, and alkaline (basalts and their differentiates)
3. oceanic intra-plate settings—mantle plumes (ocean islands) → tholeiitic and alkaline (basalts and their differentiates)
4. Continental intra-plate settings—mantle plumes (continental flood basalt provinces, continental rift zones, special potassic, and ultrapotassic volcanics, kimberlite volcanism) → tholeiitic and alkaline (basalts and their differentiates).

Intrusive igneous rocks of different compositions were formed by emplacement of various kinds of magmas into the crust. The principal groups of igneous rocks are often classified by their increasing SiO_2 (in wt.%) contents as ultrabasic (< 45), basic (45–52), intermediate (52–63) and acid (> 63) and by their increasing FeO-MgO contents.

In terms of total alkalis vs. SiO_2 contents, igneous rocks can be divided into two principal magma series: (a) the alkalic and (b) the sub-alkalic; see the discrimination line in Figure 1. Each of these series contains a complete rock suite ranging from basic to acid members. The sub-alkalic series can be further subdivided into (i) calc-alkaline (or high-alumina) and (ii) tholeiitic (low K-tholeiitic) sub-series using an AFM diagram (Figure 2).

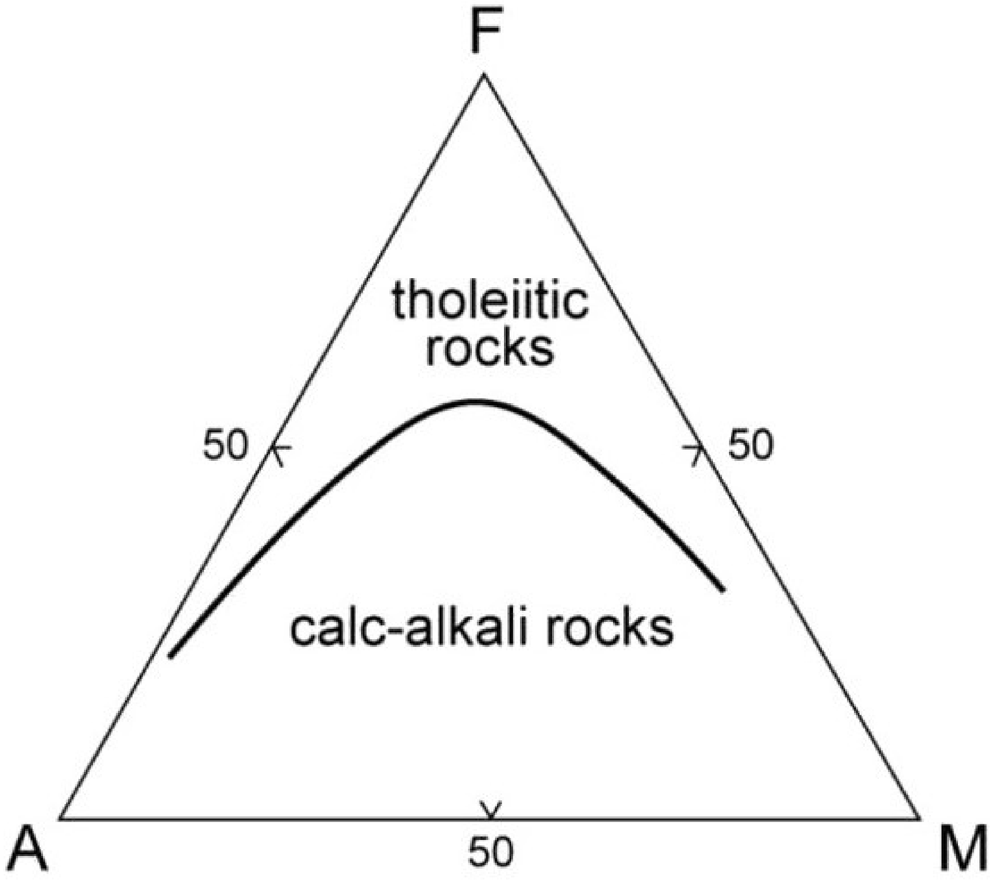

Figure 2. AFM discrimination diagram showing typical tholeiitic and calc-alkaline fields (A = $Na_2O + K_2O$; F = $FeO + Fe_2O_3$; M = MgO in mol.%).

3. Forms of Plutonic and Subvolcanic Bodies

The forms of deep magmatic intrusions are mostly poorly known and can be studied only from indirect evidence gained long after the rocks cooled and after they were uplifted to the surface and exposed by subsequent erosion. The surface and shallow subsurface (subeffusive) forms of igneous masses of volcanics can be deduced from direct geological field-work evidence or from mines and boreholes.

3.1 Abyssal Bodies

Intrusive rocks and their bodies are divided into two groups. Huge abyssal bodies crystallized in deep crustal conditions are called batholiths or plutons while smaller hypabyssal or subvolcanic bodies including dykes were formed in shallow crustal conditions. Dykes (and vents) facilitate the connection of (hyp)abyssal bodies with the surface products of volcanism (volcano-plutonic formation).

Plutons exhibit different forms and relations to the country rock which they intrude. They are formed prevalently by coarse-grained rocks, granitic in composition. Plutons include batholiths, lopoliths, stocks, and so on. Magma rises through the crust in several ways. It breaks off blocks of rocks and assimilates them. Stoping is a term applied by the geologist Daly to a process in which magma rises by breaking off joint blocks, detaching and engulfing pieces of the country rock. Batholiths represent the largest three-dimensional plutons. They are discordant to the wall rocks, forming bodies of large extent (over 100 km^2). Batholiths of granitic composition occur commonly in all orogenic mountain ranges, but are primarily present in the Precambrian shields. A lopolith is a large body emplaced into deeper crust, mostly concordant to the country rocks, and forming a bowel-shaped intrusion with a central feeding channel. Discordant subvertical smaller intrusions roughly circular in a horizontal plane are called stocks (the term is also used for similar smaller forms of subvolcanic bodies). Layered and banded structures are often present as a consequence of slow cooling and gravitational settling of dark minerals (pyroxene, amphibole, etc.). Some batholiths have a sharp thermal contact with their country rocks. Other batholiths (plutons) are characterized by an irregular contact displaying numerous apophysal, finger-like projections following the structures of the adjacent metamorphic rocks. Such contacts support transformistic ideas of the origin of granitic (and other) massifs by selective mobilization processes. The transformistic school suggests that granitization of primary sediments or metamorphic rocks and their conversion to rocks of granitic composition occurred by means of selective partial melting of crustal material and penetration of fluids rich in alkalis and gases into the surrounding rocks.

3.2 Subvolcanic Bodies

The uplift and erosion of ancient volcanoes exposed their shallow roots, which were once up to about 10 km below the Earth‘s surface. Sills, laccoliths, and dykes in particular represent subvolcanic or hypabyssal volcanic forms. A sill has a tabular form and is formed by injection of magma mostly into layers of sedimentary or other foliated rocks (metamorphic or magmatic) in an approximately concordant form. The thickness of such sills ranges from several centimeters to hundreds of meters. The rocks forming sills crystallized at depths in comparison to sheets of effusive rocks, and due to their slower rate of cooling, they are rather coarse-grained. Their thermal contact-metamorphic effect is also stronger. Laccoliths are concordant lens-shaped injections of magma along bedding planes of sedimentary formations or schistosity of metamorphic rocks. The magma nevertheless forms loaf-like or mushroom-like bodies, unlike the tabular body of sills. Laccoliths exposed after denudation form the most characteristic hills of the volcanic landscape. Dykes are typical two-dimensional flat bodies discordant to the country rock. They penetrate along pre-existing joints or fractures, always due to active forces of the magma. Prominent dykes (mostly of basaltic composition) can be traced for tens of kilometers. Dyke thicknesses vary from centimeters to tens of meters. Steeply dipping rock dykes, in particular, often form swarms of hundreds to thousands of dykes of similar strike, or fan-like distributions of dykes around a volcanic center. Thick dykes (hundreds of meters to one kilometer in width), arcuate or circular in plan view, which are vertical or outwardly inclined from the central focus of an intrusive center, are called ring dykes. Similar thin, gently to steeply dipping sheets (forming a downward-pointing cone) inclined towards a common center are termed cone sheets. Cone sheets and ring dykes are associated to form a ring complex.

The opening of the Earth‘s surface through which volcanic materials are extruded is called a vent (feeder, chimney). A neck is a vertical pipe-like intrusion that represents a former volcanic vent. The term is usually applied to the form as an erosional remnant. A pipe (chimney) is a vertical conduit below a volcano, through which magmatic materials have passed. It is usually filled with volcanic breccia and fragments of older rocks. A plug is a vertical pipe-like body of magma that represents a conduit to a former volcanic vent. A diatreme is a vertical pipe-like body filled with volcanic breccia or contains both brecciated and massive igneous rocks, and which was formed by a gas-rich explosion.

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Biographical Sketches

Jaromír Ulrych was born in Prague in 1943 where he subsequently started to live and became educated. He studied at the Faculty of Sciences, Charles University in Prague—geology with special reference to mineralogy and petrology and he received his MSc. in 1965 and his RNDr. and Ph.D. in 1975. After brief contracts on assistance at the Charles University, his scientific activities (PhD.) became associated with the Academy of Sciences, Prague, and focused on petrology of plutonic rocks of the Bohemian Massif and European Variscan terranes. In 1982 he changed the Academy for pedagogical activities at the Charles University for nearly 15 years. At present, he is engaged with the Academy again and teaches at the University as an external Associate Professor. Since 1970s, his scientific activities have been orientated on geochemistry, petrology and mineralogy of rock-forming minerals of the Cenozoic volcanic rocks of the Central European Volcanic Province. A major part of his 200 published papers and communications deal with geochemistry and petrology of magmatic rocks.

RNDr. Vladimír Cajz was born on November 23, 1959 in Praha, Czechoslovakia. He graduated at the Charles University in Praha as geologist in 1984. Since this year he had been working in the Czech Geological Survey as research geologist specialized on the Tertiary volcanics of the Bohemian Massif, and since 1993 as a Chief Geologist of the České středohoří Mts. volcanic range. Since 1999 he has been employed with the Geological Institute of the Academy of Sciences of the Czech Republic. His professional experience includes volcanology, volcanostratigraphy, volcanic petrology and geochemistry, volcanic carstology, environmental geology and processes - slope movements in volcanic rocks, volcanic monuments and their protection, protection of natural resources. Projects undertaken by him include detailed geological survey of the Cenozoic volcanics, co-operation in exploration for raw minerals, scientific projects in the Czech Republic and of the international character, too; co-operation in International Project (IUGS), etc. He also took part at the University courses as invited teacher: Geological Mapping Camp and the course of volcanology. He is a member of the Czech Geological Society, Head of the geological section of the Museum Society in Ústí nad Labem, Member of the organizing commitees of the international workshops: Symposium on Central European Alkaline Volcanic Rocks (1991), Magmatism and Rift Basin Evolution (1998), and Pseudocarst in Volcanics (1996, 1997). He is an author and co-author of 30 published papers, 8 sheets of detailed geological maps, 1 monograph and about 25 unpublished reports until 2000.