# ROCK-MAGMA AND ROCK-SPECIES

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ABSTRACT

A discussion of two fundamental petrologic terms. The word *magma* has lost its former physical significance and become a mere sack-name for any hot silicate fluid. This has led to misunderstanding of the actual physical state of the igneous fluid at the moment of intrusion or extrusion. The extravagant multiplication of rock names leads the writer to offer a definition of *rock-species* and to advocate the use of phase-petrology.

## 1. ROCK-MAGMA

The word *magma* has a long history. Apart from its ancient Greek connotation (fruit pulp?), it was used for several centuries in pharmacy with the meaning of a paste of solid and liquid matter such as *magnesia magma* or milk of magnesia. From pharmacy the word passed into chemistry. It was included in Thorpe's *Dictionary of Chemistry* as late as the edition of 1922, with the definition "a paste or semifluid mixture." It was therefore a purely physical term, denoting a state of matter without regard to its origin or chemical composition.

About the middle of the 19th century this word began to be used by geologists in place of the older expressions "surface lava" and "subterraneous lava," which had been used from the time of James Hutton. The borrowed word was employed at first with strict regard to its physical connotation, but in the course of time this connotation has been forgotten and to most geologists "magma" means only "fluid rock substance," regardless of its physical condition. This is an unfortunate state of affairs, for it leaves us without any special term to indicate a partly crystalline lava, and what is worse, it opens the door to misunderstanding of the properties of intrusive igneous matter.

The first geologist to realize that lava is typically not a homogeneous liquid but a suspension of solid particles in a liquid medium was George Poulett Scrope, English volcanologist. In the first edition of his *Considerations on Volcanos* (London, 1825), Scrope wrote that

> "The liquidity of lava, even at the moment of its protrusion from the orifice of a volcano, is extremely imperfect and of a very peculiar character. There is no reason for supposing it to be a homogeneous liquid like water or the metals and earths in a state of complete fusion. On the contrary, every circumstance in its conduct and composition shows its analogy to those compound liquids, such as mud, paste, milk, blood, honey, etc., which consist of solid particles deriving a certain freedom of motion amongst one another from their intimate admixture, in greater or less proportion, with one or more perfect fluids which act as their vehicle."

This statement is no less than a claim that lava is a magma in the physical sense, although the word magma was not used. But in the second edition of this book, which appeared under a slightly different title (*Volcanos, the Character of Their Phenomena,* etc.) in 1862 we find the terser statement that

> "lava is not a homogeneous liquid such as any melted or completely fused substance, but a *magma,* or composed of crystalline or granular particles to which a certain mobility is given by an interstitial fluid."

This is the conclusion reached by an experienced volcanologist from his own observations on Mount Vesuvius in one of its most active periods, and on other Mediterranean volcanos. Scrope's opinion was accepted in full by the master petrographer, H. Rosenbusch, who in the latest edition (1908) of his *Mikroskopische Physiographie* wrote

> "Eine Lava ist im Momente ihres Ergusses nicht eine reine schmelzflüssige Lösung, sondern eine schmelzflüssige Lösung in welcher grössere oder kleinere Mengen ausgeschiedener Mineralien in idiomorpher Begrenzung schwimmen." (A lava at the moment of its extrusion is not a pure melt but a melt in which larger or smaller numbers of idiomorphic crystals are already swimming).

Among recent writers who seem to have overlooked the historic meaning of the word magma are F. F. Grout, who has said that "the term magma primarily denotes a liquid," and P. Niggli, who defines magma as "eine glutheisse molekulare Lösung." But both writers admit that some crystals *may* be present in magma. A. K. Wells (1949), says only that "lava is molten rock material—magma—poured out through a vent or fissure." The most complete repudiation of the historic meaning of magma was pronounced by H. H. Read in 1947. In opening a symposium on the origin of granite (Ottawa, 1947) Read said:

"The igneous rocks are those produced by consolidation of *magma,* which is completely fluid rock substance." Since gas is excluded from consideration, the expression "completely fluid" can only mean completely liquid. Before we accept a definition so flatly opposed to the teaching of Scrope and of Rosenbusch, let us see what evidence we possess regarding the physical condition of the "stuff of which the igneous rocks are born" (Bowen's phrase).

(1) Various observers have recorded visible crystals in flowing lava, notably leucite and augite, on Vesuvius, and olivine, on Hawaii. Scrope himself pointed out that "the scoriform crust which rapidly congeals on the surface of a current by exposure to the open air, is found to possess the same crystalline texture, and to contain the same proportion of larger or minute crystals, as the innermost parts of the current" (1825, p. 21). This observation would be difficult to explain unless the larger crystals were already in existence before the crust was formed.

(2) About many volcanos of the more explosive type there are deposits of "crystal tuff," consisting largely of idiomorphic crystals, often of moderate size, of various minerals (especially plagioclase, augite, leucite, even hornblende and biotite) which must have been set free by the explosive dispersion of the liquid matrix in which

they grew. The summit of Mt. Vesuvius at the present time is strewn with myriads of perfect little augite crystals. Scrope recorded that after the eruption of Etna in 1669, "aeriform explosions succeeded from the same orifice, and continued to be discharged with violence during fourteen days. The fragmentary matters eructed by them produced the large cone called Monte Rosso, near Nicolosi, and covered a circuit of about two miles radius with a deep deposit of black sand containing innumerable separate crystals of augite" (1825, p. 152).

(3) Porphyritic texture is characteristic of lavas in general, and it has always been held to indicate two periods of crystallization, the large crystals (insets) having been formed before the lava reached the surface. In some basalts it has been observed that the augite insets carry thin mantles of pigeonite, while the groundmass in which the insets lie contains pigeonite as the only pyroxene. The explanation must be that the augite crystals were formed before the pigeonite and under different physical conditions, the change of conditions coinciding with the extrusion of the lava. (This observation, recorded long ago by Rosenbusch, has lately been repeated by G. A. Macdonald in Hawaii.)

(4) Even the most glassy of lavas, when examined in large bodies, will often be found to contain scattered crystals. Scrope wrote, of obsidian flows, that "whatever crystals appear embedded in these rocks, rendering them porphyritic, are clearly not of subsequent formation, but existed in them prior to the emission of the lavas, as is proved by their broken and half-fused state" (1825, p. 117). To the writer, the most striking demonstration of this fact is given by Pele's Hair, which consists of threads of perfectly transparent basaltic glass formed by the drawing-out and almost instantaneous chilling of droplets of intensely hot lava, shot into the air by the lava fountains of Kilauea. Here and there on the threads one may see tiny beads or swellings, and the microscope often reveals idiomorphic crystals or rounded grains of olivine, less commonly crystals of magnetite, in these beads. T. A. Jaggar showed that the temperature of the lava in the fountains may reach 1350°, so even at that excessively high temperature the lava contained a few crystals.

In view of this evidence, it will surely be conceded that some lava (certainly), much lava (probably), and even all lava (possibly) is already a suspension of crystals in liquid—a magma in the original sense of the term—at the moment of its extrusion. Perhaps this is not, in itself, a matter of great importance, but it raises a very important question, namely: what is the physical condition of deep intrusive matter, the "subterraneous lava" of Hutton? Is it hotter or cooler than surface lava? Is it a homogeneous liquid or is it a magma?

Many geologists, impressed by the geothermal gradient in sedimentary rocks, have assumed that active lava too must grow hotter downwards. But although sedimentary rocks, starting at atmospheric temperature, become hotter downwards, it does not in the least follow that lava with a surface temperature of 1000° must also grow hotter downwards. At Kilauea, Jaggar was able to show that the surface of the lava received much heat from burning gases, and that the temperature of the lava a few feet beneath the surface was sensibly lower than that of the surface layer. It seems impossible that basalt at 1000° can grow hotter downwards, because the common rocks of the earth-crust begin to soften and melt at temperatures of that order. Sosman and Merwin (1913) found that the arkose that underlies the Palisades diabase was more than half melted in 75 minutes at 1100–1150°; and Greig, Shepherd and Merwin observed (1933) that a specimen of powdered granite became half liquid in one week at 800°. It must follow that a deep-seated reservoir of basalt, at a temperature of more than 1000°, would inevitable melt and dissolve its walls until the contents of the reservoir no longer had the composition of basalt. Yet the enormous outpourings of basalt in the Deccan, the Columbia River region, and the Parana basin show no significant change in composition from the earliest flows to the latest.

Great dikes, sills, laccoliths and batholiths give no evidence of very high temperature. The 1000-foot sill of the Palisades did not even begin to melt the invaded Triassic arkose. Many diabase dikes in South Africa contain fragments of granite which have not been vitrified or appreciably corroded, although similar inclusions in surface basalt flows are often half-melted (e.g. Parícutin). The evidence of the peridotite-serpentine dikes which cut coal seams in Pennsylvania, and enclose fragments of coal, is very significant. From the comparison of these enclosures with pieces of the same coal heated in the coking furnace, R. B. Sosman (1938) found it possible to assert that the intrusive fluid can not have been much hotter than 520°. Sosman assumes this fluid to have been a mush of olivine crystals in a watery matrix. One is reminded of the remarkable olivine-bearing rock which was called "maimechite" by Moör and Sheinmann (1946). This is a strongly banded dike rock, some of the bands being rich in olivine crystals while other bands are largely and in some cases completely glassy. The discoverers claim with reason that the intrusive matter was "a viscous mass containing a considerable quantity of olivine crystals."

Useful evidence may also be obtained from the study of texture. In some dikes there is a marked orientation of tabular feldspar insets parallel to the walls of the dike, indicating that these insets were present in the magma at the time of intrusion. H. Winkler (1949) has pointed out that in the Cleveland dike of the north of England the plagioclase insets are "as well developed and of the same size" in the chilled margin as in the centre of the dike; from which it must follow that these crystals were present in the magma when it was injected. A similar observation was recorded by R. A. Daly (1912) in the Rock Creek porphyry of British Columbia, the insets of anorthoclase and augite having the same dimensions in the chilled margin as in the central parts of this great dike.

In the case of really deep intrusions we have to rely on the "geological thermometer" method of study. The entire absence of any evidence of the quartz-tridymite transformation, among deep-seated intrusions and their contact rocks, limits the maximum temperature of intrusion to little more than 870°. The presence of wollastonite at some granite-limestone contacts and its absence from others seems to restrict the temperature of emplacement of granite to the region of 500–550°. A well-developed porphyritic texture is characteristic of very many granites, and it is sometimes possible to demonstrate that the history of the large feldspar insets has been different from that of the groundmass feldspar (Shand, 1949).

We seem to be justified in concluding that *all igneous matter, within such levels of the earth-crust as are exposed to observation, was at the time of its emplacement a magma in the physical sense and not, or only in rare instances, a homogeneous liquid.*

It remains to indicate the importance of the conclusion we have just reached. In the first place, it has been assumed in certain theories of the earth that deep-seated igneous rocks have been generated by superheated liquids that are able to "melt and stope" their way up through the crust. Now a homogeneous liquid may be superheated to any degree short of vaporization or decomposition, but a mush of crystals in their mother-liquid cannot be superheated. If deep rock-magma is such a mush, then there can be no such thing as a superheated liquid in the higher levels of the lithosphere. Yet many outstanding petrologists have written about "superheated magma."

Though it cannot be superheated, a rock-magma may nevertheless be fluid through a considerable range of temperature. A quantitative illustration may be found in Bowen's study of the melting phenomena of the plagioclase feldspars. A mixture of the composition $Ab_1An_1$ is completely liquid at 1450°. With moderately slow cooling it will be half crystalline at 1386°, three-quarters crystalline at 1282°, seven-eights crystalline at 1164°; thus the possible range of temperature, for this anhydrous feldspar magma, is of the order of 300°. The liquid phase in this system is rather viscous so one cannot be sure at what temperature fluidity will cease, but with a less viscous fluid it is only necessary to have enough liquid present to act as a lubricant between the crystals. It does not seem fantastic, then, to suggest that a granitic magma, saturated with water, may be fluid through a range of temperature of something like 800° down to 500° or less. Thus many problems of igneous intrusion are capable of solution without the assumption of superheat.

A second instance of faulty reasoning, resulting from forgetfulness of the physical constitution of a magma, may be found in the attempts that have been made from time to time to compare the density of a particular kind of rock with that of a particular magma, in order to decide whether enclosed blocks of the rock in question should sink or swim in the magma. Since the density of natural rock-magma cannot be determined directly, the practice has been to melt a rock of the appropriate composition, chill it to the state of glass, and measure the density of the glass. But such a glass is free from crystals, while natural rock-magma, as we have seen, may contain anything from a few crystals up to perhaps 90% of crystals. Thus the density of a granitic magma (if it is permissible to speak of the "density" of a mixture of solid and liquid) must lie between that of average granite (2.66, according to Daly) and that of rhyolitic glass (2.36, according to Tilley); and any computation based on the assumption that granitic magma has a fixed density, can have little value. In any case, if the magma is far advanced in crystallization, the factor which determines whether an inclusion shall sink or float may be mere mechanical obstruction by the mass of interlocking crystals.

Surely we have said enough to show that the loose use of "magma" to mean merely "rock-forming fluid," without consideration of its physical state, is to be deplored. Yet, as an anonymous Briton has said:

> "It is a cursed thing, but true, that if a sufficient number of people speak wrongly a sufficient number of times, their wrong speech becomes right."

So there is little reason to expect that petrologists in general will renounce their slackness in the use of "magma." The most one can hope for is that they will bear in mind that although rock-magma is fluid rock substance, only a minor part of it need be liquid. The properties of the magma are largely determined by the presence of crystals in it and by the proportion of crystals to liquid.

## 2. Rock Species

If the term "magma" has been misused by petrologists, what shall we say about "species"? We have at present some 700 rock names of specific character, yet we have no accepted definition of what constitutes a rock species. Exactly 50 years ago C. R. van Hise wrote these words:

> "The method of petrographers in giving names, so far as any method is discoverable, is to give an independent name to each rock which is slightly different from any previous rock found, without regard to any definite plan."

These words are as true today as they were 50 years ago. Five new names have lately been added to the list of pyroxenites and peridotites, which already included 66 names. The leucitic lavas of Western Australia are strikingly similar to those of the Leucite Hills in Wyoming, for which Cross introduced three specific names, yet the discoverers of the Australian lavas felt it necessary to introduce four entirely new names. Where is this practice to end? If the same procedure were followed in the classification of animals, then every mongrel dog and every alley cat would be a new species on the ground that it is "slightly different" from the last one seen!

The difficulty of defining a species is not confined to petrology. An eminent zoologist has laid it down that "a species is what a competent systematist considers to be a species." But which of us is a competent systematist, and how do we know? Of the thirty or more classifications of rocks that have been proposed in the past 50 years, not one commands general acceptance. In the absence of agreement among petrologists, the writer offers his own definition of a rock species, as follows:

(A) A rock species is a group of rocks formed under similar physical and chemical conditions.

(B) Two rocks belong to the same species if both contain the same dominant minerals (with some latitude for ionic substitution) and if no phase in one rock is incompatible, either chemically or physically, with any phase in the other rock.

Examples of physically incompatible minerals are the following pairs: tridymite-microcline, tridymite-muscovite, sanidine-muscovite, leucite-microcline, leucite-muscovite (both minerals in each pair being primary). Examples of chemically incompatible minerals are the following pairs: quartz-olivine, quartz-feldspathoid, hypersthene-feldspathoid, muscovite-aegirine, anorthite-aegirine (both minerals in each pair being primary).

Both chemical and physical incompatibility are indicated, in magmatic rocks, by such associations as pyroxene-tourmaline and olivine-tourmaline.

(C) Differences in the relative proportions of phases do not yield new species but only *facies*. These should not receive distinctive names but only adjectival prefixes, as leucocratic syenite, melanic gabbro, etc.

(D) Differences in texture, except that between holocrystalline and hypocrystalline (or plutonic and volcanic) rocks, do not yield new species but only *varieties* which should be distinguished by the appropriate adjectives, porphyritic, poikilitic, pegmatitic, granophyric, etc.

Reconsideration of the existing 700 "specific" names, in the light of these propositions, would result in the immediate elimination of more than half of the names in question and perhaps, after fuller consideration, of half of the remainder.

The admission that petrology is a province of physical chemistry should be enough to condemn out of hand not only the old "natural history" type of classification but also the type that depends entirely on bulk chemical analysis. Several attempts at a classification of the latter kind were made in the early days of petrology, before the microscope came into use; but Justus Roth, who compiled the first large collection of rock analyses (1861), rejected the idea that any progress in understanding the genesis of rocks could be made by bulk analysis alone. Yet the idea was revived by Osann in 1899, by the authors of the Norm system in 1903, and by Niggli in 1923. Undoubtedly a systematic tabulation of rock analyses has many uses—few people can have made more use of Washington's *Tables* than the writer—but a tabulation of analyses is a very different thing from a classification of rocks. A chemical system consists of components, which enter into the system, and phases, which crystallize out. To discuss a rock in terms of components, without regard to phases, is just as unsatisfactory as it would be to discuss language in terms of sound without regard to sense.

As a step toward the petrology of the future, the writer (1942) has used the method of "phase petrology" (in full, *critical phase petrology*). This method depends on the recognition of certain phases, each of which has some special significance for the interpretation of the cooling history of a rock complex. Of course every mineral has some significance for this purpose, but some have more than others. From the early days of petrology an exaggerated importance has been attached to the feldspars; yet the feldspars tell us relatively little about the cooling history of a magma because they are very stable minerals which occur in almost all possible associations and within a wide range of temperature. Certain other minerals have a narrower range of stability and consequently afford more information about the physical and chemical conditions that prevailed and the changes that took place during the crystallization of a magma. These are critical phases, and the following examples may serve to indicate their use.

The presence of tridymite or leucite, and especially the association of leucite with a siliceous glass, indicates an unusually high temperature at the time of their formation.

The presence of microcline, low-quartz, tourmaline, aegirine, or muscovite indicates a temperature about the lower limit of the magmatic range.

The presence of feldspathoids, melilite, olivine, indicates a deficiency of $SiO_2$ in the system.

The presence of melilite, melanite, scapolite, cancrinite, probably indicates contamination of the system with limestone.

The presence of cordierite, andalusite, corundum, common garnet, and perhaps hypersthene, indicates contamination with alumina or aluminum silicate.

The presence of alkali-pyroxene or alkali-amphibole indicates an excess of sodium ions over aluminum ions in the system.

The presence of amphibole, mica, tourmaline, epidote, indicates reduced temperature and increased concentration of $H_2O$.

In the Cortlandt complex of New York State the most abundant minerals are plagioclase, augite, and hypersthene, but these minerals tell little of the history of the complex because they occur almost everywhere in it. On the other hand, prismatic hornblende, poikilitic hornblende, olivine, and spinel are restricted to certain regions in the complex, and a map showing the distribution of these critical phases conforms better to the structure, and gives a clearer picture of the history, of the complex than the older type of map based on the concept of natural rock species.

The method of critical phases is used in metamorphic petrology. A geologist studying a region of metamorphic rocks does not set out with a rigid concept of "natural species," but he traces the distribution of critical phases which indicate changes in the intensity and character of metamorphism. The classic example is the mapping of chlorite, biotite, garnet, staurolite, kyanite and sillimanite zones by G. Barrow in the Scottish Highlands.

Igneous petrology must undergo drastic changes. The period of collecting strange-looking specimens and inventing new names for them is over, one hopes. Our new duty is to study the accumulated data in the light of physical chemistry, to distinguish the important from the incidental, and to remember that the purpose of scientific classification is not to make a catalog of oddities but to help in the discovery and expression of natural laws. This requires the abandonment of old ideas about natural rock species, petrological affinity, spontaneous differentiation, and the like, and an increasing reliance on physical chemistry, until it is realized by everybody that petrology is the very root and trunk of geochemistry.

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