20. *The NATURAL CLASSIFICATION of IGNEOUS ROCKS.*

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CONTENTS.

	Page
I. Introduction.....	470
II. Factors of Chemical Composition.....	473
III. Factors of Magmatic Differentiation	478
IV. Classification by Eutectics	485
V. Factors of Mineral Composition	489
VI. Factors of Rock-Texture	490
VII. Quantitative Classification.....	493
VIII. Summary	503

I. INTRODUCTION.

IN how far may the systematic classification of igneous rocks, the basis of their petrographic description and nomenclature, be constructed by the application of truly 'natural factors'? This question has long been debated, but petrographers have not reached agreement as to the answer. Meanwhile petrographic system has become greatly confused through varying views as to what are 'natural relations,' and by the illogical or inconsequent use of arbitrary factors. It seems useless to hope for agreement in this matter until the petrographers of different schools have come to understand thoroughly each other's points of view, which are based largely on experience in widely separated fields of work. It is with the idea of promoting in some measure this mutual understanding, that I offer this discussion to the Geological Society of London.

The rocks of the earth exhibit a great variety of relationships of geological importance, as to their origin, their mode, form, and place of occurrence, and possess, in many groups, a complex and often obscure character. The rock is usually defined with emphasis on its geological importance, and it is considered as a geological unit. But there has not always been the desirable clear distinction between the rock-mass, of certain relations of form or position with regard to the earth, and the substance of the mass, the rock proper.

From various standpoints of geology classifications of rocks have been set up, more or less refined, for special or general purposes. All of these classifications are of use so long as their generalizations agree with experience, but manifestly they cannot be all combined in the one scientific systematic classification of petrography, from which the rocks derive their specific names. There must be various classifications of rocks or of rock-masses,

from the purely geological side,¹ but there should ultimately be but one petrographic system, based on thorough knowledge, comparable with that of zoology or botany.²

In recent years there has been much discussion as to the proper basis for the systematic classification of igneous rocks. In this discussion the adjectives natural, arbitrary, and artificial are often applied to current or proposed bases of classification. In common, I presume, with all other petrographers, I should be glad if a petrographic scheme of classification were possible to which the term natural might be appropriately applied. But I do not believe that such a system is possible, and, further, it seems to me that the systems devised for igneous rocks during the last century are unnatural, and without good reasons for most of their artificial or arbitrary features. Certain American colleagues, who entertain similar beliefs, have united with me in the formulation of the 'Quantitative System for the Classification of Igneous Rocks,'³ in the construction of which several factors prominent in earlier systems have been ignored. Some of these discarded factors are corner-stones in the systems advocated by believers in a possible natural system. In current criticism of the Quantitative System it is commonly called arbitrary or artificial, with the implication or direct assertion that a much more nearly natural system is in existence or may reasonably be hoped for. With a desire to contribute to the general discussion of this important question, as well as to explain once more my personal point of view, which led me to join in proposing the Quantitative System, I wish to present some considerations as to the availability of the natural relations of igneous rocks as factors in their systematic classification.

It may be well, however, before taking up this subject, to call attention to some general considerations which are no doubt in the minds of many petrographers but should be regarded by all, in discussions of classification. First may be mentioned the importance of definite names for rocks. Our use of a name should imply a certain meaning in our own consciousness, and the use is certainly without desired effect if the same significance is not conveyed to others. This necessitates a definition, which, in the case of a rock

¹ W. Cross, 'The Geological *versus* the Petrographical Classification of Igneous Rocks' Journ. Geol. Chicago, vol. vi (1898) p. 79.

² The obscure character of many igneous rocks on the one hand, and the need for a nomenclature based on external characters, where chemical and microscopical study is impossible, on the other hand, seems to render a field-nomenclature advisable. Such a scheme has been proposed by Cross, Iddings, Pirsson, & Washington, and elaborated by L. V. Pirsson in a textbook intended for the field geologist and mining engineer; but such a classification is clearly not for the petrographer as a specialist. 'Rocks & Rock Minerals' 1908, pp. 414.

³ W. Cross, J. P. Iddings, L. V. Pirsson, & H. S. Washington, 'Quantitative Classification of Igneous Rocks' Journ. Geol. Chicago, vol. x (1902) pp. 555-690, and in book form, Univ. of Chicago Press, 1903.

or other systematic unit, means a precise statement of the qualities characterizing it. Petrographic nomenclature must be based on a universal scientific system of classification in order that general discussions concerning rocks may be fruitful, as well as for the sake of convenience and clearness in description. There are reasonable grounds for the suspicion that many petrographers of to-day have a very hazy idea of what they mean in using most rock-names. The reader of petrographic literature is often quite uncertain as to the real character of rocks named, but not fully described.

All petrographers should realize that when they advocate 'a natural classification' of igneous rocks, or refer to existing usage as 'natural,' in any particular, they must mean according to the nature of those objects. Yet the relations assumed to be natural are actually, in most cases, merely empirical formulæ long since shown to have limited application. Only generalizations without known exceptions in experience can be applied to the construction of a system that may be called natural. Let us have regard for things as they are, not assume them to be as we wish they were, or as it would be convenient to have them.

A classification of natural objects worthy of acceptance as the systematic scheme for a branch of natural science must be logical and consistent in construction. As numerous logicians and philosophers have pointed out, a systematic classification must be constructed by the use of factors vitally related to the differing properties of the objects to be classified, and their application should follow the order of their importance. A scientific specialist should not be satisfied with a system which is such only in the mechanical plan of its construction, or with one which does not apply to all objects of the class in question.

With these principles in mind it appears to me that most classifications of igneous rocks must be called unnatural and illogical or unscientific in construction. These defects arise from two principal causes. In the first place, what has been found or believed to be true of the rocks of a petrographic province, or of a certain group, has often been too quickly assumed to be true of all igneous rocks, and an erroneous factor has been thereby introduced into the system. The age distinction, for example, seemed natural to Continental petrographers, while British geologists knew it to be unnatural, in the light of their observations. Such assumptions are perhaps unavoidable in the early history of a science, but the time must come when they should be rigorously tested in their application to the rocks of the whole earth. In the second place, it has been the practice of many of the most eminent petrographers to assume as true certain relations of rocks which were known to be but approximately in accordance with observed facts. The assumptions that texture is a function of depth, or of pressure, or of a eutectic mixture, illustrate this point. It is usually, in such cases, the convenience

of the would-be systematist which is regarded, and the resulting scheme cannot be permanent.

The first step in all current petrographic systems may be called a natural one. Igneous, sedimentary, and metamorphic rocks are grand divisions made in recognition of the intimate relation between the most important characters of rocks and certain great earth-building or modifying processes. The further use of geological factors in the classification of each grand division must depend upon their suitability for this purpose.

Chemical composition, mineral constitution, and texture are, in this order, the generally recognized natural properties of igneous rocks available for their classification. The chemical characters are certainly fundamental, and most closely connected with the molten condition. Are the chemical differences of igneous rocks clearly determined by a geological factor which may be used in the next step in classification? It does not seem to me that such is the case, but that is the crux of this discussion, and I desire to consider the actual, that is, the natural, relations of rock-characters to mode of origin or geological occurrence, and compare these with the assumptions current in petrographic system.

II. FACTORS OF CHEMICAL COMPOSITION.

The chemical composition of igneous rocks as a class is now fairly well known. No one can safely question the fact that the great majority of rocks belong to a category in which there is gradation in composition from one type to another. Even the extreme chemical types are no doubt connected with the average rock by a continuous series, although some units may be, as yet, undescribed. Classification on a strictly chemical basis is, then, necessarily arbitrary or artificial, and a natural classification that is to express the fundamental chemical characters of igneous rocks must rest on facts of genesis, or of occurrence vitally related to the known features of composition.

Origin of differences of composition.—The observed differences in chemical composition of magmas may be due to several causes:

- (a) Primeval differences in the composition of the earth's crust at different places. These variations are necessarily difficult to define, and are hypothetical as to origin. They must be expressed as facts of distribution.
- (b) Magmatic differentiation,—by which a homogeneous magma has split up into component parts of differing composition.
- (c) Assimilation,—by which a given magma has been changed in composition through the fusion and absorption of unlike material.

The first of these possible causes is quite hypothetical, and not certainly distinguishable from the others in its effects. Probably it would be most prominently visible in the geographical distribution of chemically different rocks. It is not intended to imply

that the observed variation in composition of the rocks of different parts of the earth is of this origin.

Differentiation and assimilation are in a measure antithetical processes. The former must proceed by laws; the latter is not related to the former in any definite way, and its effect may be regarded as determined by chance. Assimilation is not uncommonly assumed to have occurred in masses open to our examination and at the place where the rock is now seen. My own experience leads me to question the correctness of this assumption except in rare instances, but it is difficult for me to conceive that fusion does not take place at lower levels. If assimilation occurs within a magma-basin where differentiation has been in progress, it may affect only products of that basin, and thus merely disturb the ordinary sequence of descendant magmas. But if other materials, such as sediments, deeply infolded or faulted, should be dissolved by a magma and assimilated, it is plain that the composition of the new solution may be radically changed. Quartzite, limestone, shale, or old volcanic rocks of different composition would modify the character of an assimilating magma in very different ways, and quite independently of the earlier history of that magma.

If the ideas of isostatic adjustment within the earth's crust, by lateral flow of magma, now receiving much support from geophysicists, are correct, it appears quite possible that magmas of a given character may be moved to places where they may attack and assimilate materials of different character. When this new molten solution resolves by differentiation into parts, the products may be notably different from those which would have formed under the earlier conditions.

If the deep-seated magmas of large volume have acquired their various chemical characters in different ways, it appears at once evident that this primary genetic factor cannot be used in classification, unless the characters of different origin can be distinguished in the rocks. It seems to me clear that the antithetical and wholly independent processes of differentiation and assimilation cannot be recognized in their resultant rocks, except in the relatively rare cases where they occurred at places subsequently revealed to our examination.

If certain rocks can be recognized as deriving their chemical characters from magmatic differentiation (or from assimilation), it is logically possible to introduce this factor into classification by a primary division into: (*a*) rocks due to magmatic differentiation (or to assimilation); and (*b*) rocks not demonstrably of such origin. But such a proposition would hardly be seriously considered as suitable for general petrographic system.

Despite the inherent difficulties of genetic classification, many attempts have been made to render systematic classification natural by using factors of origin and occurrence, and it is now desired to review the various propositions of this kind.

Classification by geographical distribution of chemically different rocks.

If the igneous rocks of the northern and southern hemispheres, or of the several continental masses, differed radically in chemical composition, with no or but few common types, we might use this fact as a primary means of classification, even if the reason for such differences were not understood. But the rocks exhibit no such sharp limitations in occurrence, although certain notable features of distribution have been pointed out. Some attempts have been made to introduce these factors into petrographic system.

The Atlantic and Pacific kindred.—In 1892 Iddings pointed out that rocks rich in alkali seemed to be abundant in certain parts of the world and rare in others,¹ outlining to some extent their distribution. Later, Harker commented on the correspondence of the areas characterized by the alkali and subalkali groups with the broad Atlantic and Pacific basins, and suggested a kind of correlation between these magmatic facies and crustal movements.² But this vague distinction of chemical groups first assumed systematic importance through the proposition of Becke³ to distinguish the Atlantic and Pacific 'Sippen' or kindred, which is, in fact, as he states, an attempt to provide brief and convenient terms for cumbersome expressions used by Rosenbusch and his followers to designate the 'foyaitic-theralitic' and 'granitodioritic and gabbro-peridotitic' magma series. These series are really based upon chemical differences, and will be referred to again. Aside from the question as to whether such a primary chemical division is justifiable, the use of the terms Atlantic and Pacific, in the manner suggested by Becke, implies a generalization as to facts of distribution to which there is such a multitude of exceptions that its expression in system is unwarranted.

It may be true that the lands adjacent to the Atlantic Ocean are richer in the so-called alkali-magmas than those bordering the Pacific, but existing data concerning large areas involved in this generalization are very meagre, and the question has never been discussed in print with the thoroughness which it deserves. This is manifestly not the place for extended comment on this matter, but I wish to point out certain facts among many which might be cited as bearing on the problem.

Bohemia, the younger rocks of which country Becke strangely selects as representing the Atlantic kindred, lies between Hungary and Germany. The great series of volcanic rocks of the former country are admittedly typical of the Pacific kindred; and Germany, though exhibiting many rocks of both series, is particularly the land of the Pacific lamprophyres—minette, kersantite, vogesite,

¹ 'The Origin of Igneous Rocks' Bull. Phil. Soc. Wash. vol. xii (1892-95) pp. 89-213 (pp. 183, 184).

² 'The Natural History of Igneous Rocks' Science Progress, vol. vi (1897) pp. 12-33.

³ 'Die Eruptivgebiete des Böhmischen Mittelgebirges & der Amerikanischen Andes' Tscherm. Min. Petr. Mitth. vol. xxii (1903) pp. 209-65.

spessartite, odinite, etc., which, according to Rosenbusch, indicate the presence of deep-seated parent magmas of the Pacific kindred.

As to the North American continent, Iddings¹ once remarked that alkali-rocks occur more abundantly along the eastern base of the Rocky Mountains than in the Great Basin and along the Pacific Coast. I do not know that this is the basis for Prior's² statement that it 'has been noted that the eruptive rocks in the United States become more and more rich in soda as one proceeds from west to east,' but an examination of Washington's tables of analyses shows some peculiar facts of distribution which hardly support the latter generalization.

It seems that the analysed rocks of the Pacific coast are dominantly alkali-calcic and those of the eastern Rocky Mountain zone more strongly alkalic. But this difference appears less striking than the predominance of soda-rocks on the Pacific coast. In fact there are at least a dozen rocks of the Pacific coast, from Alaska to Southern California, which show a greater excess of soda over potash than appears in any rock of Montana, Wyoming, Colorado, or New Mexico. Conversely there are no rocks on the Pacific coast so rich in potash as the leucite-rocks of Wyoming. Some of these soda-rich rocks are also high in lime, but others are so clearly alkalic rocks that they must be referred to the 'Atlantic kindred' of Becke. Some of the more striking occurrences are indicated in the following table, with a few other rocks on which comment will be made:—

<i>Rock.</i>	<i>Locality.</i>	Analysis shows				Norm has			
		SiO ₂ .	CaO.	Na ₂ O.	K ₂ O.	An.	Ab.	Or.	Ne.
Quartz-porphry (Turner).	Plumas Co., Cal.	72.77	2.47	4.95	0.34	12.5	41.9	1.7	0.0
Soda-rhyolite (Palache).	Berkeley, Cal.	75.46	0.95	6.88	1.09	1.7	58.2	6.7	0.0
Aplite (Turner).	Mariposa Co., Cal.	74.21	1.71	7.62	0.10	5.3	63.9	0.6	0.0
Soda-syenite porphyry (Turner).	Tuolumne Co., Cal.	67.53	0.55	11.50	0.10	0.0	95.4	0.6	0.0
Soda-syenite (Becker).	Treadwell Mine, Alaska.	63.01	2.66	10.01	0.39	4.4	83.3	2.2	0.6
Carmeloite (Lawson).	Carmelo Bay, Cal.	52.83	7.35	6.61	2.52	10.8	35.6	15.0	11.1
Essexitic andesite or trachydolerite.	Crater of Haleakala, Hawaii.	49.55	7.01	6.12	2.29	14.5	34.1	13.3	9.4
Essexite (Rosenbusch).	Salem Neck, Mass.	47.94	7.47	5.63	2.79	13.9	25.7	16.7	11.9
Augite-teschenite (Fairbanks).	Point Sal., Cal.	49.61	10.05	5.62	1.04	23.9	23.1	6.1	13.3
Teschenite (Fairbanks).	Cuyamas, Cal.	50.55	7.30	8.37	2.27	11.7	17.8	13.3	28.7

¹ 'The Origin of Igneous Rocks' Bull. Phil. Soc. Wash. vol. xii (1892-95) p. 184.

² 'Contributions to the Petrology of British East Africa' Min. Mag. vol. xiii (1901-03) p. 261.

A large proportion of the dominant alkalicalcic rocks of California are very rich in soda as compared with potash—a much larger proportion than among the rocks of the Rocky Mountains. The Pacific coastal zone appears to be a soda-rich province, as compared with the Rocky Mountain portion of the United States.

Another distinction which seems notable from a study of Washington's tables is that on the Pacific coast high silica goes with high soda, so that foyaitic magmas, nepheline-rocks, are rare, especially among persalanes and dosalanes. In the *solfameane* class there are some nepheline-bearing rocks, as illustrated by three cases of the foregoing table. These belong, of course, to the Atlantic kindred, with the *essexite* of Salem Neck, which is included in the table for purposes of comparison.

These facts regarding the rocks of the Pacific zone of North America indicate, I think, that they possess provincial peculiarities of interest; but these are not by any means identical with the features emphasized by Becke and others as characterizing the Pacific kindred.

The dominance of soda over potash is also very strong in all rocks from the Hawaiian Islands thus far analysed; and several of these belong to the 'Atlantic kindred' of Becke, including trachyte,¹ melilite-nephelinite basalt, and others usually but not well called basalt, such as the one from the crater of Haleakala, collected by myself, which has in part the composition given in the foregoing table. This rock contains but 2.49 per cent. of magnesia. It is evidently very near the typical *essexite* in chemical character, for which reason I apply to it the name '*essexitic andesite*' in the table (=trachydolerite).

The broad underlying significance of these facts of geographical distribution postulated by Harker, Becke, and independently by Prior,² has been touched upon by these authors. Becke points out that the Pacific kindred of young volcanic rocks seem to be connected with mountain-chains representing folding under tangential stress, according to Suess, while the Atlantic kindred occur on lines of fracture through radial contraction. Whether this is true or not (and it certainly needs confirmation and elucidation) the relationship involved is not that responsible for the chemical differences of the magmatic series; nor does it appear that the generalization of distribution applies to the older rocks. Thus in the Great Rift Valley of East Africa, the rocks of which have been so well described by Prior, the younger foyaitic-thermalitic series of magmas of the Atlantic kindred are underlain by old crystalline granites, gabbros, *para-gneisses* and other rocks, which from Prior's descriptions seem to belong to the Pacific kindred. The same relations probably exist in the Bohemian Mittelgebirge, the volcanic rocks of which are

¹ W. Cross, 'An Occurrence of Trachyte on the Island of Hawaii' Journ. Geol. Chicago, vol. xii (1904) pp. 510-23.

² 'Contributions to the Petrology of British East Africa' Min. Mag. vol. xiii (1901-03) pp. 228-63.

made by Becke the type of the 'Atlantische Sippe,' for granites, gneisses, gabbros, minettes, kersantites, and other igneous rocks of the adjacent Erzgebirge are certainly of the contrasting kindred. Systematic classification is, however, not for Tertiary rocks alone.

Petrographic provinces.—The interesting and significant 'blood-relationship' shown by the rocks of certain cycles of eruption in many petrographic provinces, or comagmatic regions, is clearly not adapted to systematic purposes. Many types are common to various provinces, and the peculiar characters of a province are seldom, if ever, so fundamental as the properties uniting the rocks of different provinces. The type of consanguinity may be marked only for the products of an epoch of eruption, rather than for all rocks of a province, as seems to be the case of the East African region above mentioned.

III. FACTORS OF MAGMATIC DIFFERENTIATION.

General considerations.—I suppose that all present-day petrographers recognize magmatic differentiation as a general process by which many of the observed chemical differences in igneous rocks must be explained. In numberless volcanic centres there is evidence of a sequence of lavas, by no means uniform, but resulting in final complementary products of rhyolite and basalt. In certain masses, like the Shonkin Sag laccolith, made classic by Pirsson, the differentiation has occurred after intrusion, and we may see the results; in many localities a large central mass is attended by numerous smaller bodies, the clanship of which and their derivation from the main magma are demonstrable.

The recognition of magmatic differentiation as a natural phenomenon involves no acceptance of theories of explanation. It is already clear that effects comparable in kind are produced by the operation of various processes. When the complexity of the magmatic solution and the multiplicity of conditions to which it may be subjected in the eruptive history of a single centre are borne in mind, it appears certain that we can as yet have but a faint conception of the true character of what we include under the term magmatic differentiation.

The recognition of this vague but undeniable natural phenomenon has furnished to some petrographers an all too alluring opportunity for speculation and assumption, and on the other hand it has suggested a most difficult and extensive field of physico-chemical research. The genesis of igneous rocks is manifestly destined to be an important department of petrology and a fundamental element of the general science of geology. We are here concerned, however, with the special question whether the systematic classification of igneous rocks can be made natural, in one of the primary steps, by the use of a genetic factor connected with differentiation.

The now general beliefs that magmas are essentially mixed solutions, and that most igneous rocks represent differentiation-products, render the conception logical that all igneous rocks may

be derived from one homogeneous earth-magma. The only escape from this lies in the assumption of hypothetical primary differences in the earth-mass.¹ Rosenbusch¹ and many others doubtless assume the original homogeneity of the earth-magma. Differentiation in the abstract might be used as a systematic factor, if we knew the composition of the supposed primordial magma, and if we were sure that the composition of that magma could never be repeated by the mixture of differentiates. But such division of rocks is not likely to be proposed, for divers evident reasons.

Aschistic and diaschistic magmas.—Differentiations may lead to a general distinction between parent magmas and their derivatives, passing over the supposition that the great differences in composition of parent magmas themselves are due to differentiation. This would be making a general division corresponding to that which Brögger has found useful between the parent magma of a given centre and the partial magmas derived from it, and expressed by the respective terms aschistic and diaschistic.²

The introduction of this distinction into general system would be difficult and of doubtful utility. Thus the parent magmas of various regions, or centres of eruption, differ so much that the early differentiates of one would certainly be practically identical with the parent magma of another centre; many rocks do not visibly belong to a series, and the personal equation would necessarily enter into many cases where judgment is necessary. For these and other reasons no proposition of this kind is likely to be made.

The 'dyke rocks' of Rosenbusch.—Leaving general considerations, we now come to the definite proposition of Rosenbusch to distinguish the class of 'dyke rocks,' really on a genetic chemical basis, though this is obscured by the name. Here is opportunity for a discussion touching practically all phases of the problem as to the application of chemico-genetic factors in petrographic system.

For the analysis of this important proposition it will be well to have before us the most recent definition of the 'dyke rocks' as a systematic division. In the 4th edition of the 'Mikroskopische Physiographie: Massige Gesteine' vol. ii, pt. i (1908) pp. 487, 488, is the following:—

'Als Ganggesteine bezeichne ich nur solche Eruptivmassen welche als selbständige geologische Körper nach dem augenblicklichen Stande unserer Erfahrungen nur in typischer Gangform und im Vergleich zu den Tiefengesteinen geringer Masse des einzelnen Gesteinskörpers auftreten. . . . Die stoffliche Natur der wichtigsten Ganggesteine ist [dagegen] bedingt, nicht durch diese selbst, sondern durch gewisse Tiefengesteine, an die sie gebunden sind und ohne die sie nicht sein würden.'

¹ 'Ueber die Chemischen Beziehungen der Eruptivgesteine' Tscherm. Min. Petr. Mitth., vol. xi (1889) p. 144.

² 'Die Eruptivgesteine des Kristianiagebietes, I: Die Gesteine der Grorudittinguait Serie' 1894 (Vidensk. Selsk. Skrifter, I. Mathemat.-Naturv. Klasse No. 4) p. 125.

The positive assertion of limited association enters also into the definition of many of the kinds of 'dyke rocks.' As an example may be cited the statement concerning camptonite:—

'Alle Gesteine vom Camptonittypus gehören als Ganggefolge zu den foyaitischen und theralithischen Tiefengesteinen und verhalten sich zu Bostoniten, Tinguaiten u.s.w. wie die Minetten, Kersantite, Vogesite, u.s.w. zu den Apliten.'¹

It is well also to remember that Rosenbusch considers magmas as made up of one or more stoichiometric compounds, called by him Kerne, some of which are mineral molecules, while others are not. Further, it is essential to consider that Rosenbusch refers the principal magmas which have developed by differentiation from a homogeneous earth-magma, through the separation of the Kerne, to two contrasting series, the 'granito-dioritic and gabbro-peridotitic' and the 'foyaitic-theralitic.'

Before entering upon the critical discussion of this matter, I wish to repeat a former statement that

'I must not be understood as failing to appreciate the great advance in our knowledge of the origin of igneous rock varieties and of their structures, and of the genetic relationships of types which has come within the past few years largely as a result of . . . the theoretical ideas [of magmatic differentiation] lying back of the systematic scheme advocated by Rosenbusch. One may well deny the desirability of the Dike rock group of Rosenbusch and be at the same time an ardent advocate of the [genetic] theories upon which the group was established, and which have little connection with the fact of geological occurrence expressed in the name.'²

The inappropriateness of the term 'dyke rocks,' as used by Rosenbusch, may be passed over here; nor is the weakness of the 'Kerntheorie' proper of great significance in itself. The elaborate review of the latter by Brögger reaches an important conclusion, however: namely, that in the theoretical discussion of magmatic differentiation the 'Kerne' of Rosenbusch must be replaced by molecules common in the minerals of igneous rocks, and that the number of these is somewhat greater than that assumed by Rosenbusch for the 'Kerne.'³ Brögger's discussion seems to me quite convincing, and the conclusion is certainly in harmony with the facts of the rocks and of modern researches on molten solutions. Iddings advocates the same view in the discussion of differentiation, in his recent work on igneous rocks.

A peculiar feature of the 'dyke rock' group of Rosenbusch deserving examination here is the asserted exclusive association of certain kinds with particular deep-seated parent magmas, from which alone they could have been derived by magmatic differentiation.

¹ 'Mikroskopische Physiographie: Massige Gesteine' 4th ed. vol. ii, pt. i (1908) p. 685.

² 'The Geological *versus* the Petrographical Classification of Igneous Rocks' Journ. Geol. Chicago, vol. vi (1898) pp. 89-90.

³ 'Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolge des Laurdalits' 1898 (Vidensk. Selsk. Skrifter, I. Mathemat.-Naturv. Klasse, 1897, No. 6) p. 332.

Vitally connected with this is the asserted existence of two great magma series. Let us examine the latter point first.

The magmatic series of Rosenbusch are unnatural.—At the outset I must deny that the ‘granito-dioritic and gabbro-peridotitic’ and the ‘foyaitic-theralitic’ series are natural. They are both arbitrary and ill-defined. Magmas of corresponding silica-contents in the two series are connected by intermediate ones, just as are the parts of each series. An examination of Washington’s tables of rock-analyses, particularly if they are studied and compared by use of the norms there given, will show this gradation. From the theoretical side, viewing magmas as mixed solutions of rock-mineral molecules, it is difficult to see any reason why the two series of Rosenbusch should not be connected at all points. The fact that the distinction is both arbitrary and indefinite makes it easy for those who wish to do so to assign magmas one way or the other, just as syenite and diorite were easily and conveniently separable until the uncomfortably logical Brögger demanded recognition of the equally important intermediate monzonite.

Rosenbusch is forced to recognize that monzonite occupies in some respects what he regards as a rare or peculiar (*eigenartige*) position between his two great magmatic series. But he claims that those who (with Brögger) put monzonite in a series monzonite-banatite-adamellite miss the natural relationships.¹ It is difficult for me to understand why the position of monzonite and essexite as intermediate in more than one direction should not be recognized. The existing chemical data clearly show this broader relationship.

As we are discussing natural classification as necessarily based on the facts of nature, it is here an appropriate place to point out that the ‘dyke rock’ division of Rosenbusch loses one of its most strongly emphasized peculiarities if the dual series just discussed are arbitrary.

The restricted association of ‘dyke rocks.’—As to the sharply restricted association of ‘dyke rock’ types, asserted by Rosenbusch and made a part of their definition in many cases, no one of wide experience can fail to recognize the kernel of significant truth in this generalization. Some rock-types are much more abundant in certain associations than in others. The more rare and peculiar it is in composition, the more likely is a rock to be restricted as a magmatic differentiate; and, conversely, certain parent magmas must inevitably transmit certain prevalent characters to their descendant parts. But with differences in parent magmas must come variations in the prevalence of derived characters and in associations of descendant forms.

It is difficult to present the evidence that many ‘dyke rocks’ have not the restricted genesis assigned to them by Rosenbusch

¹ ‘*Mikroskopische Physiographie: Massige Gesteine*’ 4th ed. vol. ii, pt. i (1908) p. 166.

in a form which will convince the partisans of that belief. To quote from an experienced correspondent on this matter:—

‘If you show that there is no large mass to connect the dykes with, they say it is underground and not exposed by erosion; if you present evidence that this is improbable, then the province is an alkalic one anyhow and such rocks are to be expected. If you show that the dykes are associated with a kind of rock different from what was to be expected, you are informed that you are mistaken; that you have not understood the real nature of the rock-mass, that it is, for example, not a diabase or gabbro, as hitherto regarded, but really an *essexite*. Or, if the parent mass is too plainly fixed to shift its base, then you are mistaken in your idea of the dykes—they are not actually *camptonite*, but a variety of *spessartite* with brown *hornblende*!’

This situation arises from the indefinite, arbitrary distinction between the two magmatic series above discussed.

Certain ‘dyke rocks’ of Colorado.—We may pass now to a specific case of notable exception to the rule, postulated by Rosenbusch, that *bostonite*, *camptonite*, and *monchiquite* magmas belong exclusively to the ‘*Gefolgschaft*’ of *foyaitic-theralitic* parent magmas. In the Engineer Mountain quadrangle of South-Western Colorado there occur several thin *laccoliths* and *sills* of a rock which I call ‘*quartz-trachyte*.’ In the immediate vicinity are numerous small dykes of typical *monchiquite* and some of the *camptonitic* rocks, and others. While the region is rich in all manner of Tertiary igneous rocks of the ‘*granito-dioritic series*’ there are none of the ‘*foyaitic-theralitic series*’. No analysis has been made of the *monchiquite*, but the *quartz-trachyte* has the composition stated in column I of the following table, while in column II is tabulated the analysis of the typical *bostonite* of Marblehead Neck (Mass.). In adjacent columns are tabulated the calculated norms of the two analyses.

TABLE OF ANALYSES AND NORMS.

<i>Analyses.</i>			<i>Norms.</i>	
	I.	II.	I.	II.
SiO ₂	70.73	70.23	Quartz	19.6
TiO ₂	0.34	0.03	Orthoclase	33.4
Al ₂ O ₃	14.22	15.00	Albite	41.9
Fe ₂ O ₃	1.59	1.99	Anorthite	...
FeO	0.59	undet.	Corundum	0.8
MnO	0.11	0.24	Femic molécules ...	3.8
MgO	none	0.38		4.1
CaO	0.72	0.33		
Na ₂ O	4.96	4.98		
K ₂ O	5.57	4.99		
H ₂ O—	1.16	0.91		
H ₂ O+	0.32	1.28		
P ₂ O ₅	0.03	0.06		

I. Quartz-trachyte, Grayrock Peak, Engineer Mountain quadrangle (Colorado). Analysis by George Steiger.

II. Bostonite, Marblehead Neck (Mass.). Analysis by T. M. Chatard.

The quartz-trachyte is nearly identical chemically with the type *bostonite*. The name chosen expresses the fact that it has a strong textural resemblance to *trachyte*, since it contains numerous tabular

phenocrysts of sanidine and a few flakes of biotite, in a trachytic fluidal holocrystalline ground-mass. The quartz occurs only in interstitial particles.

The intrusive bodies of this trachyte occur in various sedimentary formations, the youngest being of late Cretaceous age, and side by side with quartz-monzonite porphyry bodies, typical of rocks widespread in the Rocky Mountain and Plateau provinces. The monchiquite dykes, some of which cut the quartz-trachyte, are all small, rarely exceeding a few feet in thickness.

In immediate association with the two rocks already mentioned are other lamprophyric types, some of which are camptonitic; others are nearer to kersantite and minette.

A few miles south of the quartz-trachyte area, in the La Plata Mountains, are camptonitic dykes associated with a large number of intrusive dioritic, monzonitic, and syenitic rocks in laccolithic or stock intrusions. The La Plata Mountains are in fact one of the laccolithic groups, like the Henry, Abajo, Carriso, El Late, and Rico Mountains, where the same types of alkalicalcic magmas occur in closely comparable manner. That these dyke rocks are chemically camptonitic seems evident from the following table of analyses and norms. Mineralogically they contain abundant brown hornblende, partly in large phenocrysts, with more in the ground-mass. The principal feldspar is a plagioclase.

ANALYSES AND NORMS OF CAMPTONITES.

	<i>Analyses.</i>					<i>Norms.</i>			
	I.	II.	III.	IV.		I.	II.	III.	IV.
SiO ₂ ...	47.25	43.98	44.22	42.73	Orthoclase .	15.0	9.5	10.0	12.8
Al ₂ O ₃ .	15.14	13.30	12.73	14.50	Albite	17.8	15.7	17.8	21.0
Fe ₂ O ₃ .	5.05	3.67	5.68	4.03	Anorthite ...	22.8	21.7	20.3	19.2
FeO ...	4.95	6.92	5.18	7.28	Nepheline...	1.4	1.4	...	2.8
MgO ...	6.87	7.03	6.98	5.46	Diopside ...	21.4	25.5	24.0	16.9
CaO ...	9.98	10.66	11.57	8.46	Hypersthene ...	...	...	4.7	...
Na ₂ O ...	2.39	2.15	2.12	3.11	Olivine	7.2	9.3	3.1	6.8
K ₂ O ...	2.60	1.64	1.71	2.28	Magnetite...	7.4	5.3	8.4	5.8
H ₂ O+ .	2.12	1.52	2.74	3.08	Ilmenite ...	2.3	2.3	4.8	8.3
H ₂ O- .	0.40	0.42		0.36	Apatite	...	...	2.5	2.5
CO ₂ ...	1.87	6.46	3.66	3.76					
TiO ₂ ...	1.22	1.18	2.50	4.30					
P ₂ O ₅ ...	0.25	0.32	1.05	0.93					
MnO ...	0.17	0.22	0.45	0.19					

Complete analyses show small amounts of other constituents.

- I. Camptonite, Snowstorm Peak, La Plata Mts. (Colo.). Analyst, W. F. Hillebrand. Bull. U.S. Geol. Surv. No. 168 (1900) p. 162, and La Plata Folio.
- II. Camptonite, Indian Trail Ridge, La Plata Mts. (Colo.). Analyst, W. F. Hillebrand. Bull. U.S. Geol. Surv. No. 168 (1900) pp. 162-63, and La Plata Folio.
- III. Camptonite, Kjøse-Aklungen, Norway. Analyst, V. Schmelck. W. O. Brögger, 'Die Eruptivgesteine des Kristianiagebietes, III: Das Gangfolge des Laurdalits' 1898, p. 51.
- IV. Camptonite, Mount Gunstock (New Hampshire). Analyst, H. S. Washington. 'Chemical Analyses of Igneous Rocks' Prof. Paper No. 14, U.S. Geol. Surv. 1903, pp. 318-19.

To me the occurrence of the rocks described in Colorado seems incompatible with the idea of their exclusive association with foyaitic-theralitic magmas, although I grant that experience shows them to be elsewhere frequently connected genetically with such magmas.

The general relations of camptonite occurrences.—Examining the statements of Rosenbusch concerning the distribution of camptonite, in his ‘*Physiographie*,’ we find the frank avowal that the derivation of the original type camptonites of New England from foyaitic magmas was inferred by him from their frequent association with bostonite. But not all of these rocks occur in close connexion with foyaitic-theralitic magmas. Rocks of the granito-dioritic series also occur in the region. The original camptonites described by Hawes are many miles distant from the nearest occurrence of alkalic rocks at Red Hill, and no alkalic parent magmas are known in connexion with them. The numerous dykes of camptonite described by Kemp and Marsters are much nearer to the great anorthosite and gabbro masses of the Adirondacks than to any foyaitic bodies. Camptonite and bostonite or keratophyre also occur in the Adirondacks.

Rosenbusch asserts that the lamprophyric dyke-rocks of the one great series are never connected with those of the other by transitional forms, and in accordance with this belief assigns all rocks described to a definite place. It is manifestly impossible to determine in the field the genetic association of many camptonites, bostonites, kersantites, and aplites. From the vast amount of evidence that the two magmatic series are connected by equally abundant intermediate magmas, I can but believe that the sharp distinction between the two ‘dyke rock’ groups is a purely arbitrary one, resting on an unproved hypothesis.

Conclusion as to ‘dyke rocks.’—Our present knowledge of the processes of magmatic differentiation is too slight to permit a definite assertion, that from a given parent magma certain differentiates must be formed. But it is reasonable, I think, to suppose that typical foyaitic, monzonitic, and dioritic magmas, subjected to the same conditions, must produce differing series of descendant partial magmas. It does not necessarily follow that those series must be markedly different in all their members. If different conditions attend the differentiation of the magmas, the resultant partial magmas may not fully correspond to those formed under uniform conditions.

Given an intermediate monzonitic magma, is it not natural to suppose that its descendant magmas must be intermediate in many respects between the series derived from foyaitic and dioritic parent magmas, and that a shifting of conditions may throw the dominance of characters either one way or the other?

IV. CLASSIFICATION BY EUTECTICS.

Recognition of the fact that magmas are solutions implies the existence of eutectic mixtures in them. The low melting-point of the eutectic suggests that partial crystallization necessarily brings the residue of the magma nearer to the eutectic proportion in composition. The study of magmas in the light of physical chemistry has, then, naturally led certain investigators to hope that in this relatively new field of rock-properties there may be something available for fundamental genetic or natural classification. Becker, Vogt, and Harker have made the most important suggestions in this direction.

Becker's suggestion,—G. F. Becker was the first to express the idea of classification by eutectics.¹ He regards the eutectic as the solvent in the magmatic solution and hence of greater importance than the variable materials in excess, which, in porphyries, are developed as phenocrysts. This idea is not in accord with the conception now current that the magma is a mutual solution of its several components. The following quotations indicate the way in which Becker would use eutectics in classification, and the special purpose subserved by so doing:—

‘ If we knew all about magmas, it seems fairly certain that we could define a number of eutectic mixtures, each, when heated above its melting point, yielding an infinite variety of solutions corresponding to rocks of an infinite variety of compositions.

‘ From this point of view the groundmass of rocks would be more interesting and important than the phenocrysts, while it has usually been studied with less care, because of the greater difficulties in the way of mineralogical determination. The groundmass would either consist substantially of the eutectic mixture, or afford a closer approximation to it than does the whole rock.

‘ It is difficult to imagine that the comparatively small number of elements which enter largely into the composition of massive porphyritic rocks should form any very great number of independent eutectic mixtures; and it seems to me that it would be possible to elaborate a eutectic classification of those rocks which have consolidated from the liquid state—I mean the porphyries—each rock-group representing a series of solutions in one eutectic liquid. Such a classification would also have certain geological advantages over others, for the composition of the groundmass of rocks largely determines their orogenic significance.

‘ Even among the rocks which represent solidified fluids there is a class not subject to such a classification as is here proposed. It seems an inevitable conclusion from the laws of precipitation that there must be many rocks which have been formed by fractional crystallization.

‘ Now, such fractional precipitates are essentially impure. Either in nature or in the laboratory, they represent neither the substance dissolved nor the solvent or mother liquor, but only fortuitous mixtures of the two—crystals of precipitate, including and entangling variable quantities of mother liquor; crusts, which vary in composition from millimetre to millimetre. Rocks of such origin appear to me insusceptible of any strict classification and fit only to throw a dim light on the qualitative composition of the magma, which they represent, indeed, but only partially and irregularly. Were a eutectic classification worked out, it would probably be easy to recognize these impure partial precipitates, which would then receive the scant attention they deserve.’

¹ ‘Report on the Geology of the Philippine Islands’ 21st Ann. Rep. U.S. Geol. Surv. pt. iii (1901) pp. 487-614 (pp. 519-20).

Eutectic classification as outlined by Becker is plainly not adapted to general petrographic system. It ignores the fact that the rock is the result of the consolidation of the whole magmatic solution, except the escaped volatile constituents, and not of the eutectic alone. It is not applicable to all rocks, and would be primarily of use in purely physical discussions, such as the influence of varying fluidity of lavas upon the form of volcanic cones.¹

Vogt's proposition.—A proposition by J. H. L. Vogt² to utilize eutectics in the genetic classification of igneous rocks is combined with an hypothesis of magmatic differentiation. It must be assumed that the reader is familiar with the notable series of experimental investigations, statistical studies, and theoretical discussions which led Vogt to his conclusions as to the existence and approximate character of the eutectia of magmas. By supposing that the parent magmas of various centres are not themselves very nearly of any eutectic composition, Vogt pictures the process of differentiation to consist in the concentration of components which are in excess of the eutectic. By long-continued migration of these substances and their concentration in certain places there may result partial magmas rich in plagioclase, pyroxene, olivine, titanium and iron ores, spinel, or some other mineral. These approach the simple composition of a single mineral in many cases. The complementary result of such a process is an approach on the part of the residue of the parent magma to the eutectic mixture.

Theoretically, the differentiation pictured by Vogt should end with the production of a eutectic magma. Practically it does not, owing to disturbance of equilibrium by some external influence, and several anchi-eutectic magmas may be formed from a single parent magma, as Vogt admits.

Vogt believes that most magmas may be practically classified either as anchi-monomineralic or anchi-eutectic, and that such groups may serve as the basis of a genetic system for igneous rocks.

Although the extremely suggestive studies which have led to this preliminary proposition are of the highest importance, there are many reasons for questioning whether the genetic factors concerned are applicable to petrographic system. It is universally recognized that many genetic factors are not of systematic value.

Objection to eutectic classification may be made on several grounds. In the first place, the genetic importance of eutectia in magmas remains to be established and defined. It is no disparagement of Vogt's work in this direction to say that he deals chiefly

¹ G. F. Becker, 'The Geometrical Form of Volcanic Cones & the Elastic Limit of Lava' *Am. Journ. Sci. ser. 3*, vol. xxx (1885) pp. 283-93.

² 'Ueber anchi-monomineralische & anchi-eutektische Eruptivgesteine' *Vidensk.-Selsk. Skrifter, I. Math.-Naturv. Klasse*, 1908, No. 10; also under a similar title in an earlier publication.

with unknown quantities and processes. The parallelism between differentiation and crystallization on which Vogt depends is not an established law, attractive as it appears as a working hypothesis. The cause of molecular migration in differentiation is unknown, and there may be several causes leading to dissimilar products. No eutexia of rock-minerals are known. Vogt may have reached approximately correct proportions for some of them, but in view of the unknown influence of water and other mineralizers, of impurities of various kinds, and of a long series of changing conditions, one may be pardoned for lack of confidence in his results.

If we assume that there are ten or more important eutexia of rock-making minerals, and that these are little affected by various conditions and impurities, it is of course plain that each eutectic mixture represents a centre-point about which many rocks cluster. This must be the case whether the nearly pure eutexia are more numerous than other mixtures or not. The statistical studies of Vogt fail, it appears to me, to demonstrate that degree of quantitative dominance of the eutexia which must exist to warrant the systematic proposition made by him. The range of variation covered by the term 'anchi' (meaning almost), as used by Vogt, is so great as to destroy its significance.

When one considers the probable influence of some of the variable factors ignored by Vogt—and especially that of water—it seems not impossible that the whole fabric of Vogt's speculations may fall, with the advance of knowledge on these points.

Magmatic classification by eutectics is fundamentally weak, because it rests on hypothesis, because it does not apply to all rocks, and because it does not consider the entire magma of most rocks. As developed by Vogt it does not adequately recognize the very important rocks representing parent magmas which are not anchi-eutectic, nor the numerous intermediate rocks ('Zwischenstufen').

Turning from the magma to the rock, what stamp has the eutectic placed on the consolidation-product, justifying its use in classification? Becker's conception that the ground-mass of porphyries is practically the eutectic must be extensively qualified; and, if it were true, the conclusion that the phenocrysts are of little systematic importance is not admissible from the petrographic standpoint.

The porphyritic texture is determined by conditions of consolidation, of which approach to the eutectic proportion in the still liquid part of the mass is but one. A vast number of porphyries, both extrusive and intrusive, possess ground-masses that are simply that part of the magma which was liquid at the time of eruption. The eruptive act takes place independently of the stage of crystallization reached in the magmatic reservoir. The change of physical conditions is, in many cases, sufficient to prevent further phenocrystic growth.

Doubtless the ground-mass of many porphyries is nearly of

eutectic composition. But the most typical porphyries of my experience, the monzonitic rocks of laccoliths, sills, and dykes in the Rocky Mountain and Plateau districts of the United States, possess a ground-mass consisting chiefly or exclusively of quartz and orthoclase, while abundant plagioclase occurs in phenocrysts. Surely plagioclase ($Ab + An$) entered into the eutectic of these magmas.

I believe it to be a fact of experience that the consolidation-products of any given magma exhibit, under the various conditions of different occurrences, all possible proportions of ground-mass to phenocrysts.

The view that certain textures, such as the graphic, the spherulitic, and the felsitic, are characteristically eutectic seems to me incorrect. Intergrowth, whether graphic or spherulitic, may mean simultaneous crystallization, but I question the necessity for eutectic proportions. In any case these textures are due to physical conditions, since it must be admitted that they are by no means always developed in the presence of the eutectic.

Conclusion.—In view of the care with which a host of observers have studied all details of rocks, the world over, it does not seem to me rash to assert that the eutectic has left no stamp on the consolidated magma, the rock, with possibly a few exceptions. If we consider the mineral and textural characters of the igneous rock it appears that, in the first place, the composition of the solution as a whole, and, in the second place, the conditions influencing crystallization, such as supersaturation, mass action, rate of cooling, escape of volatile constituents, and viscosity of the magma, have had far more influence upon the rock than the character of the eutectic. The latter has itself split up into minerals which are not different in their rock-making qualities from those molecules that were in excess in the magmatic solution, and they must be in part identical. In many cases escape of mineralizers, fractional crystallization, and other influences seem likely to have so changed the character of the assumed eutectic that the magma may have had several different eutectics in the course of crystallization.

The propositions of Vogt do not seem to me to have significance as bearing on systematic petrography. He has gone far from the base of real knowledge of rock eutectics, and while his brilliant original studies and theoretical discussions have done much to advance the application of physical chemistry to the study of magmas, they do not appear to have indicated a future practical factor for petrographic system. A classification by eutectics may in the future be realized, but it seems inevitable that it must be a classification for a special interest, not for the general science of petrography.

V. FACTORS OF MINERAL COMPOSITION.

The actual mineral constitution of an igneous rock (its mode) is the second of its features in importance, because it is very largely an expression of the fundamental chemical composition and also determines many of the most obvious characters of the rock. If a natural classification cannot be based on the chemical composition, we must turn next to the mineral characters in our search for appropriate factors of systematic arrangement.

At the outset it must be recognized that mineral composition is not a simple function of the chemical constitution of the magma. Magmas of complex character may form various mineral combinations under differing conditions of crystallization. Any attempt to express chemical character through mineralogical classification must, therefore, be only an approximation.

The minerals of igneous rocks are much more numerous than the chemical elements of corresponding importance in them, and many minerals have a known quantitative range in rocks, from a trace to strong predominance. Hence systematic divisions on mineral composition are necessarily arbitrary or artificial, and the difficulties of constructing a logical system by this means are even greater than on a chemical basis.

The relationship of mineral composition to factors of genesis or occurrence is complex. Some constituent minerals of igneous rocks are formed only under a limited, and others under a much wider, range of chemical or physical conditions. Moreover, many rocks contain minerals formed at different places under different conditions, as illustrated by intrusive and effusive masses. These facts are of great importance in the natural history of the rock, but are not practical bases of systematic classification.

It is so generally admitted that all mineralogical classification of igneous rocks is arbitrary, that this point might well be dismissed here, were it not for the desirability of referring to current usage. It was once supposed that certain approximately proportionate combinations of minerals constituted groups which were much more abundant than the rocks of intermediate composition, and were thus in a measure natural units, such as granite, syenite, diorite, etc. Although no one may now maintain this position, the fact is tacitly ignored by many petrographers that these and all other terms based on mineral composition cannot be precisely defined, as is necessary for accurate and universal concordant classification of rocks, without recourse to an arbitrary quantitative factor. The necessity for sharp definition is becoming more and more evident as petrographers study the rocks of certain series in detail; and here and there the arbitrary quantitative line is being introduced into definition, but without a consistent logical basis. The outcome can but be confusion worse confounded.

The distinction between felspathic and non-felspathic
Q. J. G. S. No. 263.

rocks which has been so prominent in current system is not only unnatural, but is in the highest degree arbitrary. There is no logical consistency displayed in characterizing and treating as felspathic a rock whose predominant characters of all sorts are due to the greater abundance of non-felspathic constituents. It is done purely for the convenience of the systematist.

VI. FACTORS OF ROCK-TEXTURE.

The texture of igneous rocks is very commonly used in their classification. Let us consider whether this factor is or can be applied for that purpose, in accordance with the facts of nature.

Nature of rock-textures.—Rock-texture may be considered to embrace all the material features exhibited by the rock constituents, whether mineral particles or glass, and whether megascopic or microscopic. It thus includes a great variety of allied characters which may be conveniently brought into three categories¹:—

- (1) Crystallinity—the degree of crystallization.
- (2) Granularity—the magnitude of the crystals.
- (3) Fabric—the shape and arrangement of the crystalline and non-crystalline parts.

Texture is a physical feature, largely independent of chemical or mineral composition, produced during the consolidation of the magma into rock. The range of crystallinity is from holohyaline to holocrystalline; of granularity, from very coarse to submicroscopic; of fabric, an almost infinite variety of design with many pronounced forms and often a mingling of them in a single rock. The common grouping of textures under the heads granular, porphyritic, fluidal, or glassy, is a crude approximation to the truth, useful when applied in accordance with the facts, but often serving to obscure or conceal actual relations. A granular rock answering to the definition is rare, as compared with the aberrant forms called granular for convenience; and the porphyritic fabric is one of limitless transitions to the granular, the felsitic, the fluidal, and the hyaline.

Origin of rock-textures.—As already remarked, texture depends upon the conditions controlling consolidation. Each magma has an infinite range of possible textures representing

¹ This classification of textural features, and the general view of the subject here adopted, is presented more fully in a paper by the writer and his colleagues Iddings, Pirsson, & Washington, published a few years ago ('The Texture of Igneous Rocks' Journ. Geol. Chicago, vol. xiv, 1906, pp. 692-707). In this paper the great variety of textural features is emphasized, the paucity of adequate terms for descriptive purposes is pointed out, and a large number of new terms proposed.

varying conditions. If we perfectly understood the influence of conditions on texture we might sketch the history of each rock during its consolidation period. But chemical composition has also a general and very important bearing upon texture, in that the influence of given conditions varies with the chemical character of the magma. No set of conditions produces the same result on all magmas.

A discussion of the origin of various textures is not necessary for our present purpose. It will suffice to recall that we now know rate of cooling to be the principal factor in the production of texture, with varying results according to the composition of the magma. Rate of cooling depends on initial temperature of magma, mass, pressure, temperature, and conductivity of wall-rock, escape of gases from solution, and on other factors. Another factor of great influence in producing texture is movement of the partly solidified magma. Wherever this occurs orientation of mineral particles is a natural result.

Applying these considerations to the granular fabric, it is plain that slow cooling and uninterrupted crystallization may most commonly be expected for deep-seated masses; but, wherever the necessary conditions are realized, the granular fabric must result. Granite, once believed to be possible only as a result of crystallization at great depth, is now known to have formed also very near the surface. Dykes which penetrate a volcanic centre where long eruptions have been in progress have often the same texture as that exhibited by plutonic masses of the same rock. Basic magmas find conditions favourable to granular fabric provided in the interior of surface-flows, as well as in intrusive plutonic bodies.¹

Use of texture in classification.—Texture has always been very prominent in the classification of igneous rocks. Although its systematic application has seldom been consistent, we have, in fact, one set of names for what are stated or assumed to be granular rocks, and another set for porphyritic, fluidal, and more or less glassy rocks, which are their chemical equivalents. A general dependence of texture on conditions of consolidation was long ago recognized, and the convenient assumption was made that pressure is the principal element of the conditions favourable to the production of the granular texture. Further, pressure was considered a function of depth. The latter is true only if tangential stress and eruptive force bearing on an intrusive magma are ignored; and, as above mentioned, pressure is now known to be less potent in determining texture than a variety of other conditions.

The old idea of the relation of pressure to production of the

¹ This was recognized by B. von Cotta, who pointed out that, if the chlorite of diabase should prove to be of secondary origin, 'the whole original difference would perhaps lie in the level at which solidification took place' 'Gesteinslehre' 2nd ed. (1862) p. 84.

granular texture made it appear possible to express two important genetic relationships at once, in the distinction between Plutonic and Volcanic rocks. The former might, with a few known exceptions, be called granular, and they thus stood in marked contrast to surface volcanics, which are glassy or highly fluidal in their typical occurrences about volcanoes.

Plutonic and volcanic rocks are certainly different in texture, to a degree rendering their separation and the distinct names which they bear eminently desirable—if that were the whole story. But this procedure ignores the fact that the earth's crust for a few thousand feet downwards is, in many great mountain-tracts and in other places, characterized by a complex of igneous masses of all shapes and sizes, and representing the entire range of chemical variation. And with our present understanding of rock-texture it is easy to see that here must occur both the textures of the depths and of the surface, with others less commonly produced above or below. With this recognition of the zone of intrusion, as it is sometimes called, came as the first proposition, to make three classes: I, Abyssal (Plutonic); II, Hypabyssal (Intrusive); III, Volcanic (Effusive) rocks. This is nominally on a basis of geological occurrence. It is, however, not a natural division, as such, because there must be arbitrary lines between the Hypabyssal zone and both the Abyssal and Volcanic. If these divisions are equivalent to Granular, Porphyritic, and Fluidal or Glassy, the scheme is arbitrary, since those textures grade most insensibly into each other. It is unnatural, because the textures have no such restriction in occurrence. It is certainly illogical to make in fact a textural division while expressing one of occurrence, and *vice versa*.

Brögger frankly states that his principal object in distinguishing the Hypabyssal rocks is to make it possible to give special names to the porphyritic rocks. This he illustrates by asserting that laurvikite, rhomb-porphyry, and trachyte are three essential names for textural phases from the same magma.¹

Conclusion as to textural classification.—The plain fact is that classification by occurrence, as determining texture, or by texture, as expressing the broad phases of occurrence, is based on long disproved generalizations made from limited observation. But, like the age distinction, the unnatural connexion of texture with occurrence has so many expressions in system or nomenclature that recognition of the truth is embarrassing. Witness the treatment of many diabasic and allied rocks by Rosenbusch, classifying them at first with the plutonics, now with the effusives, yet a host of them are neither, being hypabyssal in actual occurrence. The known

¹ 'Die Eruptivgesteine des Kristinijagebietes, I: Die Gesteine der Grorudit-Tinguait Serie' 1894, p. 124.

occurrence of hundreds, if not thousands, of rocks of all kinds is disregarded by their classification in Rosenbusch's work into deep-seated or effusive rocks, to say nothing of the dyke rocks.

The connexion of texture with geological occurrence in a systematic way dates from days of ignorance concerning the origin of texture, and of very limited knowledge of the rocks of the hypabyssal zone of the earth, with their multiplicity of textural forms. Once this systematic proposition seemed a close approximation to a statement of natural relations. Now we know that it is not in accord with the nature of things; its use to-day is purely arbitrary (often a matter of personal convenience), and yet it is commonly referred to as 'natural'! This course simply serves to befog the discussion of truly natural classification.¹

To classify igneous rocks as plutonic, intrusive and extrusive, or by other equivalent terms, with the idea that because such a scheme expresses certain geological relationships it must perforce be accepted as 'a natural system,' may be compared with dividing vertebrate animals into aquatic, terrestrial, and aerial, or those that swim, walk, and fly, respectively. This division is natural in its way, and agrees with zoological system in its general results. The zoologist, however, does not call the whale a fish because it lives in the water and swims, nor the bat a bird because it flies, although it is more confined to this form of locomotion than is any bird.

VII. QUANTITATIVE CLASSIFICATION.

Introductory.—If the considerations thus far presented are well founded and sufficiently comprehensive, it appears that a natural classification of igneous rocks, expressing a relation between their most notable chemical or physical properties and the origin of those properties in geological occurrence, is impossible. The natural

¹ As an instance of recent advocacy of this systematic proposition, I would cite a paper by Dr. F. H. Hatch, 'The Classification of the Plutonic Rocks' (Science Progress, Oct. 1908), where the appropriateness of recognizing the two great divisions of plutonic and volcanic rocks is stated without further discussion in these terms:—'Apart from mode of occurrence, the difference in internal structure or texture between a eugranitic plutonic rock, that has cooled slowly as a deep-seated mass under pressure and in the presence of occluded water, and a porphyritic or semi-vitreous volcanic rock, that has been erupted at the surface and has cooled quickly, is so great that a system can scarcely be termed natural that places two such different rocks in the same category. In a natural classification, therefore, the plutonic and the volcanic rocks must be recognized as distinct classes.' (Sep. cop. p. 1.)

The necessity for a distinction on this ground is less obvious when we consider that coarsely crystalline or even granular basic rocks are known, which have cooled slowly in a surface-flow, while there are equivalent porphyritic or semivitreous rocks, which have evidently formed as a result of rapid cooling in the hypabyssal zone or below. Classification is not for granitic rocks alone, nor for plutonics, though many suggestions in classification have seemingly been made without consideration of the needs of other rocks.

history of the objects is too complex. The only remaining basis for systematic classification is in the characters of the objects themselves.

The chemical, mineral, and textural characters of igneous rocks are each gradational as regards several elements. No systematic division can be made except along arbitrary or artificial lines, and in this sense petrographic classification must be unnatural, as the units are not obvious, though no reproach necessarily attaches to the artificial scheme, since it is unavoidable in the nature of things.

Any systematic classification of rocks worthy of the terms logical and scientific must be constructed with due regard for the facts of the rocks and the relative importance of their characters. Chemical composition is the fundamental character of igneous rocks, and it seems inevitable that it must be the basis of their scientific classification. In magmas, a few chemical elements are sufficiently abundant to influence materially the character of the minerals developed. The number of minerals is somewhat greater. Whether ultimate chemical or actual mineral components are considered, the differences exhibited by rocks are mainly due to the relative proportions of the components. Any system expressing these relative proportions may be called a quantitative system, and such would appear to be the logical one for petrography under the circumstances.

This is the age of quantitative investigation, statement, and definition. Everywhere the effort of scientific men is to determine constants and make definition precise, to discard estimate, approximation, assumption, where greater exactness may be attained. Petrographic system should not lag behind.

The use of chemical composition in quantitative classification.—There are several ways of expressing the chemical differences of rocks in classification. The elements themselves, the molecules in which an analysis is commonly stated, and combinations of the latter, may be used. Since the rock, generally crystalline in some degree, is the object of classification, a scheme based on elements or simple molecules as such, is less satisfactory, less logical, than one expressing the connexion between chemical and mineral composition.

The use of the 'Atomzahl' by Rosenbusch, in certain discussions, has not appealed to many petrographers. Ratios of certain oxides or groups of molecules stated in the analysis are all more or less inadequate for the purpose, because their bearing on mineral composition is more or less indirect.

The various efforts of recent years to determine certain molecular ratios for rock-units, primarily established on a mineral basis, serve to characterize the special rocks considered; but no true system can be reached in this way, without the ultimate necessity of constructing a rigid chemical framework on some logical basis.

This would be a quantitative system, and no such scheme has been presented.

The representation by diagrams of the average composition of rocks, to which certain names are given in the current system, is valuable as illustrating the influence of chemical on mineral character. Certain characteristics of selected centre-points are thus brought out. But the intermediate centre-points have also their characteristic diagrams, and no systematic solution is reached until a quantitative basis for the units has been formulated.

The connexion between mineral and chemical composition is definite for some rocks, and approximate for most others. Hence, if the varying chemical analyses can be interpreted in terms of minerals, we can appreciate the significance of their differences. An attempt to provide such a basis of comparison has been made by Iddings, Pirsson, Washington, and myself; and I wish to discuss that proposition the more fully, because it has not been understood by many petrographers, who have viewed it entirely as a part of the Quantitative System.

The 'norm' as a means of interpreting and comparing rock-analyses.—An analysis of a fresh igneous rock gives the composition of the magma which it represents as closely as possible, the lost volatile constituents being no longer determinable. A magma on crystallization yields certain minerals; and, while the micas, amphiboles, pyroxenes, and many feldspars are complex mixed crystals, they can be regarded as composed of simpler mineral molecules, most of which may occur alone. It is possible to select a series of comparatively simple mineral molecules, into which all rock-analyses may be translated by calculation. If this is done by an invariable rule, the meaning of chemical differences in analyses is more clearly brought out than by comparing the oxides or any chosen ratios.

A definite set or series of mineral molecules was selected for this purpose by my colleagues and myself, and called by us the norm, meaning a standard of measurement or comparison. This series of molecules was not a haphazard selection from among those that might be used, nor was the procedure in calculation adopted without special reason. Chemical affinities and the laws which seem to control crystallization were regarded as far as possible, and the norm is a kind of statement of potential mineral composition of a magma. To an extent greater than we realized at first, it now seems probable that the molecules of the norm may actually be the molecules present in molten solution. Molecules with the composition of quartz, orthoclase, albite, nepheline, leucite, anorthite, corundum, diopside, hypersthene, olivine, magnetite, apatite, and others are not unlikely to exist as such in the magmas. The metasilicates of the alkalis may also be there, though entering into aemite or a similar mineral on crystallization.

The chemico-mineralogical expression of an analysis, obtained in

the norm, is found to agree very closely with the actual mineral composition (mode) of many comparatively simple rocks. Neither the norm nor any other calculated set of molecules representing minerals can correspond with the mode of most intermediate and femic rocks, for mineral composition is not a function of chemical composition alone, but is controlled largely by the varying conditions under which a given magma consolidates in different places. The molecules of the magma may form a considerable number of complex compounds, and these undoubtedly vary as the equilibrium in the solution is disturbed by changing conditions, and magmatic reactions occur.

To repeat, the norm is primarily a means of comparison, and has in itself nothing to do with system. We seem to have made a mistake in assuming that, provided we were explicit in definition, this standard could be called a norm and its adjective normative without confusion with the old term normal. Norm and normative had not been used in petrographic discussion, as far as I am aware, before their introduction by us for a special purpose. When proposing the terms norm and normative, we stated that

‘the standard minerals which make up the norm are to be called the normative minerals, not the normal ones, since the latter adjective has the meaning of usual or common.’¹

But it has been one of the commonest criticisms of the Quantitative System that we assume as normal to a rock a composition which it does not exhibit.² Such is not the case. The norm is simply a standard form of expressing the chemical analysis of a rock in comprehensible terms, which also apply to its magma. The calculation of the norms for a set of rock analyses in no wise classifies the rocks. It does assist more than any other expedient, in my opinion, in understanding the complex relation between chemical analysis as usually stated and mineral composition. An example of its use independent of system is afforded by the discussion of the analyses of camptonite in this paper.

The ‘norm’ in quantitative classification.—A quantitative classification of rocks according to chemical factors may be based on the usual analytical statement of composition, or on some other expression calculated from the analysis. If a proper expression of chemical composition in mineral terms can be found, it seems desirable to use that expression in classification. The norm was of course planned for this ultimate purpose, as well as for

¹ ‘Quantitative Classification of Igneous Rocks’ 1903, p. 147.

² The recently published brief statement of the Quantitative System by Mr. L. Fletcher, which I know must have been intended for a fair *résumé* (‘An Introduction to the Study of Rocks,’ 4th ed., 1909, p. 146), refers to the molecules of the norm as ‘imaginary’ (!). I can but deprecate the use of a term serving rather to prejudice the reader than to explain the system.

immediate comparison. If a method can be found for analysing the differences of composition expressed by the norms, the latter may serve as the basis of classification.

The 'American' Quantitative System.—The foregoing discussion was written before I had an opportunity of reading the masterly treatise on the 'Natural History of Igneous Rocks' by Alfred Harker. For that work I have profound admiration, and feel that the science of petrology has been materially advanced by this mature and progressive treatment of the major problems of igneous rocks. I can cordially agree with the author in most of his conceptions as to the natural relations of igneous rocks. In general, I subscribe to his optimistic view (*op. cit.* p. 362) that

'we have almost within grasp a fundamental principle analogous with that of descent, which lies at the root of natural classification in the organic world.'

but unfortunately see no ground for the hope that we can apply that principle in petrographic system. The laws of magmatic descent operate on such complex solutions and under such a variety of conditions, that factors of necessary simplicity and of clear application in logical system seem to me impossible of realization. The future must decide which view is correct.

It was no part of the original plan of this paper to advocate or defend the quantitative system proposed by my colleagues and myself, often referred to as 'the American system.' But it has been so severely criticized by Harker in the work just quoted, in connexion with a general plea for the 'natural' classification of igneous rocks, that a brief reply to certain points seems not to be out of place.

I will pass over such comment on the system as comes from the general objection to a quantitative as opposed to a natural system. The preceding discussion shows why the desirable natural system seems to me unattainable. The fact that Mr. Harker is able to make no definite proposition of systematic value, after his exhaustive study of the natural relations of igneous rocks, seems confirmatory of this view. The hope that in eutectics there may be found a natural principle suitable to classification seems futile, in view of the probable complexity of that relation and of other considerations, as has already been pointed out.

The general criticism of the Quantitative System that it separates similar things is inherent in any system with precise definition of units. The current mineralogical system is everywhere approaching that situation with no definite, consequent basis for its precision.

As to the basis of the system, the norm, I find a strange reluctance on the part of Mr. Harker to acknowledge that it has any merit or significance, while certain features are repeatedly referred to in terms of condemnation, as wofully artificial. The basis is alluded to as chemical in 'a disguised form,' and as 'a circuitous manner

of representing a chemical analysis.' The authors consider it 'chemico-mineralogical' and as, in fact, an indispensable interpretation or expression of the purely chemical. Mr. Harker says that the Quantitative System is based

'upon a hypothetical mineralogical composition which is not in general that of the actual rock.' (*Op. cit.* p. 363.)

The norm is otherwise called 'ideal,' and 'a certain artificially selected "standard" list' of minerals. He notes that the complex micas, garnets, aluminous hornblendes and augites, melilite, spinel, and others, are not in the norm,

'while in their place we find kaliophillite, sodium and potassium metasilicates, wollastonite, and åkermanite,—compounds which are foreign to igneous rocks, and some of which are not known in Nature.' (*Op. cit.* p. 365.)

Nowhere do I find recognition of the plain fact that the norm is almost wholly made up of substances which Mr. Harker and many others believe to be the principal simple molecules of the magmatic solution. Nor is the repeated statement of the authors of the Quantitative System that it is essentially a magmatic classification, so far as the new divisions go, emphasized as it should be.

I wish to return to the discussion of the norm in connexion with the third desideratum of an 'ideal system' presented by Mr. Harker, which it seems well to quote in full:—

'III. Since rock-magmas are mixtures of minerals, and the variation met with in igneous rocks is a variation in the associations and relative proportions of minerals, it follows that a natural classification must be in its expression a mineralogical one, not a chemical. It is true that the actual mineralogical constitution of a given magma may vary to some extent in accordance with temperature and other conditions, and this would seem to import some complication where successive differentiations have been effected at higher and lower temperatures. If it should be found necessary to represent complex low-temperature minerals by simpler compounds, these must at least be compounds which actually exist in the rock-magmas.' (*Op. cit.* pp. 376-77.)

The first sentence of this statement appears to recognize that one element in an ideal system is an expression of the relative proportions and associations of the mineral molecules in magmatic solution. The second sentence recognizes variation in molecular constitution in accordance with conditions, and the last one that complex molecules may be necessarily represented by simpler ones in any statement.

In his discussion of rock-magmas (*op. cit.* chap. vii, p. 169), Mr. Harker states that

'the constituents of a molten rock-magma exist there in the form of definite compounds, mostly silicates, and in general identical with those compounds which are familiar in the less complex rock-forming minerals.'

I find direct mention of orthoclase, albite, anorthite, leucite, nepheline, quartz (tridymite), and corundum, and must infer that

he would include sodalite, noselite (nosean), and zircon. These mineral molecules are the only ones in the salic division of the norm, by which three classes of igneous rocks are classified as far as the subrang.

Of the femic normative silicates Mr. Harker recognizes the chief: aemite, diopside, hypersthene, and olivine, as magmatic molecules, and the general rule that meta- or orthosilicates of calcium, magnesium, and iron are present in the magma in relation to the silica contents. In short, if Mr. Harker should attempt to compare magmas, in a consistent manner, by study of rock-analyses, and to express their character in terms of the mineral molecules that he believes to be in solution (see quotation above), his list must apparently be very nearly that of the norm. If the metasilicates are combined in regular proportions in diopside, hypersthene, and aemite, he will occasionally have an excess of sodium and calcium metasilicates. The latter he might prefer to call pseudo-wollastonite, the enantiotropic form of CaSiO_3 existing above 1180° .¹ He would also encounter the necessity of recognizing some subsilicate molecule for high lime contents in the magmas of melilite rocks, for the latter would be a difficult complex molecule to insert into his standard scheme.

Mr. Harker might call his standard scheme of magmatic molecules 'the norm' or apply some other term; he might use it in his ideal classification or not; but its usefulness for comparison and interpretation would, I think, be considered greater than diagrams or arbitrary ratios of oxides could be.

Apparently, Mr. Harker's reluctance to recognize the significance of the norm comes from his inference that

'the underlying idea seems to be that the constituents exist in a rock-magma in the form of free oxides, a conception which necessarily obscures natural relationships.'

This inference is perhaps not unnatural, in view of the statement by Iddings in 1892,² that oxides and not definite silicate compounds were present in the magmatic solution, and because this idea was not specifically disclaimed in the presentation of the Quantitative System. It is true that in 1902, when the System was issued, the components of magmatic solution were by no means so clearly known or indicated as at the present time. But the idea that mineral molecules were the important ones, under the conditions immediately preceding crystallization, was by no means unknown to the authors of the Quantitative System, nor were they at that time advocates of the hypothesis that the magma contained oxides and silicate compounds.

¹ E. T. Allen & W. P. White, 'On Wollastonite & Pseudo-Wollastonite, Polymorphic Forms of Calcium Metasilicate; with Optical Study by Fred Eugene Wright' Amer. Journ. Sci. ser. 4, vol. xxi (1906) pp. 89-108.

² 'The Origin of Igneous Rocks' Bull. Phil. Soc. Wash. vol. xii (1892-95) p. 158.

I do not mean to claim that our ideas in this matter were as clear as they are to-day. We may have builded better than we knew. But there was every reason why we should not go into theoretical discussion of the molecular constitution of the magma in connexion with the norm, for we laid stress on the belief that systematic classification should not be based on theory. The constitution of the magma is still imperfectly known; it was much less so in 1902. Some degree of electrolytic dissociation in magmas is assumed by Iddings, Vogt, and Harker.

Whatever our views on the magmatic solution may have been, the important point, so far as the character of the norm is concerned, is that the normative molecules were chosen after a very careful consideration of the laws of chemical affinity, which have been evident in synthetic work and are expressed in crystallization, and would control the combinations of oxides and other primary constituents of rock-magmas, whenever combination was possible. These considerations are stated very concisely, but definitely, in explaining the norm and the order of procedure in its calculation. For all the purposes of this discussion it is immaterial whether these laws become effective at crystallization or before it. The significant fact is that the laws of chemical affinity, recognized in formulating the norm, appear to have been in the main correctly understood; that they have operated in the magmatic stage, and still hold good to a large degree under the average conditions of crystallization.

The remark of Mr. Harker that the 'rangs and subrangs are made to depend directly on chemical characters, viz., the molecular ratios of certain oxides,' while other divisions rest on proportions of mineral molecules, shows that he did not understand why this was done and deserves explanation, destroying the critical force of the comment. The molecular ratios of K_2O , Na_2O , and CaO , on which rangs and subrangs depend, in Classes I, II, and III, are not the ratios of the total amount of these oxides in the rock as shown by analysis, but of that part of these oxides assigned to molecules of orthoclase, leucite, albite, nepheline, sodalite, noselite, and anorthite. In other words, the ratios are the ratios of these mineral molecules, in three groups. It is a concise and convenient way of indicating the character of the silicate molecules the proportions of which, in the groups called felspar and lenad (felspathoid), enter largely into the division of Orders. The same explanation applies to the ratios of oxides used in making rangs and subrangs in Classes IV and V. They stand for certain mineral molecules.

The view that magmatic molecules correspond to simple mineral molecules has been expressed by many petrographers. While testing the 'Kernhypothese' of Rosenbusch in its application to laurdalite and its descendant rocks, Brögger came to the conclusion that magmas consist of simple compounds ordinarily found in rock-minerals, and that their number exceeded not very greatly the

assumed 'Kerne' of Rosenbusch. He specifies orthoclase, albite, anorthite, nepheline, as molecules in which alumina is combined with silica and alkali or lime.¹

In his recent work (1909) on igneous rocks, Iddings says:—

'They [the compounds in solution] are mostly silicates, with a few oxides, SiO_2 , Fe_2O_3 , Al_2O_3 , and other non-silicates in some cases. The components do not exist as uncombined oxides, with limited exceptions.' (Vol. i, p. 268.)

The dichotomous principle on which the Quantitative System is worked out is a practical necessity, as I venture to think will be the conclusion of Mr. Harker—who objects to it—or any one else attempting to deal with a number of variables in a quantitative scheme. That the result in the Quantitative System is unfortunate is not, I believe, the general opinion of those who have applied it. Its primary effect is certainly to give appropriate form and bounds to five vague magmatic divisions ordinarily referred to as ultra-acid, acid, intermediate, basic, and ultra-basic. The course of magmatic differentiation is commonly conceived as tending to separate the femic (basic) from the salic (acid or alkalic) magmas. In this first division of common use Mr. Harker would surely not put corundum, a molecule which he recognizes as existing in some magmas, with the femic or basic constituents, although he criticizes our placing it in the salic group.²

The assertion that a unit of a quantitative system should bring together things which are alike, must have regard for the basis on which that unit is made. Mr. Harker criticizes the Quantitative System in this way by reference to the subrang Toscanose.³ The citation of the names which petrographers have given to rocks found under Toscanose in Washington's tables is not, as Harker uses it, proof of the heterogeneous character of the assemblage belonging to this subrang. The larger number of different names assigned by the current system to rocks under Toscanose were given on account of texture or occurrence, features not entering into the chemico-mineralogical definition of Toscanose. Other names cited by Mr. Harker are not properly applied to the rocks in question. Thus the 'trachytes' have a notable amount of free silica and of lime-felspar: they should be called quartz-lafite in most cases. The 'hypersthene-andesite' has in its norm 7·8 per cent. of femic molecules, 8·3 per cent. of anorthite, and 25·6 per cent. of quartz, the balance being alkali felspar; and its mode can vary from this to no great extent. The 'granites' were named before quartz-monzonite came into use, and are rich in the anorthite molecule. The 'rhyolites' all carry more anorthite than typical rhyolites should.

Instead of showing the heterogeneity of Toscanose, this list of rocks illustrates the lax and inappropriate use of terms under the

¹ 'Die Eruptivgesteine des Kristianiagebietes, III: Das Ganggefüge des Laurdalits' 1898, p. 332.

² 'The Natural History of Igneous Rocks' 1909, p. 364.

³ *Ibid.* p. 363.

old system. And, as Mr. Harker points out, the names of rocks found under other subranges have the same significance as those under Toscanose. Washington¹ found that rocks called 'granite' belong to 20 different subranges, 'trachytes' to 23 subranges, 'andesites' to 27 subranges, which is neither an argument for the homogeneity of the old group nor for the heterogeneity of the new units of definite bounds!

Mr. Harker remarks that

'the manner in which the various oxides are actually combined in the minerals—in the author's terminology, the "mode" of the rock—finds no place in the classification.' ('The Natural History of Igneous Rocks' 1909, p. 365.)

The mode naturally finds no place in the magmatic classification expressed by the new systematic nomenclature. But it is not true that the authors of the Quantitative System did not provide, by many definite suggestions, ways of stating in any given case the actual mineral and textural characters found in a given rock-unit. It is undesirable to enlarge on this subject here, but the idea of the authors of the Quantitative System may be repeated. It is that mineral composition and texture are each variable qualifying features of any consolidated magma. The ends of systematic petrography will be best met by using these characters as qualifiers in the ways which experience may show to be most effective. By these means, and only by them, I think, can the appropriate descriptive terms needed for the illimitable variations possible for each magmatic unit be connected with the fundamental chemical character.

The foregoing review of principles, of facts of nature, of points of view, will, I hope, assist in directing discussion towards the vital question, Is a natural classification of igneous rocks possible? Mr. Harker outlines the 'Desiderata in an Ideal System.' I can quite agree with him in this statement. In the abstract I should also agree with the forceful final comments on the Quantitative System embodied in these sentences:—

'The strongest objection to the Quantitative Classification is, however, that it is planned entirely on a *a priori* lines.....As von Richthofen aptly remarked, in order to establish a more natural system, we have not to make groups, but to find them.....The scheme of Nature (is) based not on arithmetical but on physical and chemical principles.' (*Op. supra cit.* p. 366.)

But these truisms and ideal characters of a natural system do not make the system. What are the physical and chemical principles practically applicable to petrographic system? Who shall find the natural groups? If the groups do not exist, if the principles are unfortunately not suitable to systematic use, then must we not come to an *a priori* basis for that classification on which specific nomenclature must rest?

¹ 'Chemical Analyses of Igneous Rocks' Prof. Paper No. 14, U.S. Geol. Surv. 1903, p. 61.

VIII. SUMMARY.

(1) A 'natural' system of classification is one giving expression to facts of nature, the plan of the system being demanded by the laws of the origin of the principal characters of the objects to be classified. Natural laws are established by facts, not by process of reasoning.

(2) No current classification of igneous rocks is, in any of its main features, in accord with the facts of nature.

(3) It is questioned whether petrographic system for igneous rocks can be strictly natural, because all their important characters are gradational within a group, and are due to complex geological conditions.

(4) The scientific logical classification of igneous rocks must apparently be based on the quantitative development of fundamental characters, and the divisions of the scheme must have sharp artificial boundaries, since none exist in nature.

(5) Chemical composition is the fundamental character of igneous rocks, but it may be advantageously expressed for classificatory purposes in terms of simple compounds, which represent either rock-making minerals or molecules entering into isomorphous mixtures in known minerals. It is probable that the magmatic solution consists of such molecules and that the norm of the Quantitative System is a fairly representative set of these compounds.

(6) The actual mineral and textural characters of igneous rocks are variable qualifiers of each chemical unit, and should be applied as such to terms indicating magmatic characters.

DISCUSSION.

Mr. HARKER welcomed this paper as a clear statement of the Author's position. He took a more hopeful view than the Author of the ultimate prospects of a natural classification of igneous rocks, and believed that in Vogt's conception of 'anchimonomineralic' and 'anchieutectic' types we had already the germ of such a system. He was content to await in patience the gradual development of a more rational classification with increasing knowledge. The conviction that this development would be seriously impeded if a rigid artificial taxonomy and terminology came to be generally adopted, was one ground for his objection to the Quantitative Classification.

The speaker thought that the authors of this system had been decidedly, if unconsciously, influenced by the now obsolete conception of a rock-magma as a mixture of free oxides, which might be arbitrarily linked together for purposes of convenience. He pointed out that, since such constituents as lime and alumina enter into ferromagnesian as well as into felspathic minerals, the choice of the 'standard' molecules may affect even the class to which a given rock is to be assigned. Thus the 'hornblendite' of Brandberget,

which on general mineralogical grounds would be ranged in *Perfemane*, appears in Washington's *Tables in Sulfemane*.

Dr. J. W. EVANS believed that a natural classification of igneous rocks must be founded on genetic principles, but admitted that our knowledge of the processes involved in the differentiation of igneous magmas was still too incomplete to enable us to frame a satisfactory permanent system of classification on these lines. It might, he thought, be possible to demonstrate the existence of rock-types which occurred with greater frequency than the intervening links, and might serve as the centres of natural groups that would prove to have a genetic significance; but the necessary detailed information as to the composition and extent of rock-masses was as yet insufficient for the purpose. In the meantime, what might be called an arithmetical classification, with arbitrary lines of division based on the proportions of different constituents, might, he thought, be of considerable value as a kind of pigeon-hole arrangement of analyses for convenience of reference. The silica percentage had in fact been widely employed in this way. In that case there was only one substance employed as an index. If, on the other hand, the proportions which one group of constituents bore to another were adopted as the basis of the classification, it was important that the increase or decrease of the associated substances in the differentiation of rocks should be determined by similar conditions. Even if it were admitted that crystallization was the predominant process in the differentiation of a magma, the eutectic theory would give us little assistance except in the more basic rocks, for up to the present it had been worked out only in anhydrous magmas. The presence of water profoundly affected the order of crystallization of the rock-forming minerals, and the succession enunciated by Rosenbusch was, he believed, an expression of the differences in the affinity of rock-constituents for water. Those with the greatest attraction for water, the 'hydrophil' constituents, if the expression might be allowed, were the last to separate from a water-bearing magma: they included silica, and the alkali feldspars and the feldspathoids. The two last-named groups, however, probably existed in the magma, in the form of silica and the alkaline aluminates which were highly soluble in water. This selective action of water appeared to operate, both in segregation by crystallization and in magmatic differentiation in the fluid state. If the hydrophil constituents had been grouped together by the American Quantitative Classification, it might have been of some service to petrologists. Unfortunately the 'salic' minerals of its authors included, not only these substances, but anorthite and any molecular excess of alumina over the alkalis. Anorthite, however, played a part totally different from that of the alkali feldspars, though it occurred in solid solution with albite as a result of community of crystalline structure. It was, as a matter of fact, essentially a basic silicate, which, unless it was present in very small amount or was 'brought down' by albite, crystallized out

before augite, and in some cases even before olivine. Anorthosite (which consisted mainly of anorthite) was more closely allied to a peridotite than to a quartz-orthoclase rock, with which the American classification associated it. Similar considerations applied in the case of an excess of alumina, which usually appeared as a constituent of augite or hornblende,¹ and should have been classed with the femic minerals. The salic group was in fact a collection of minerals which had nothing essential in common, and the fundamental lines of division of the classification were accordingly practically meaningless. Its general adoption in the description of rocks would, therefore, hinder rather than advance our recognition of their relation to one another.

Mr. T. CROOK contended that the primary requirement of a system of classification of igneous rocks was, that it should be natural. The formation of igneous rocks took place by differentiation, and was essentially an evolutionary process. Experience proved that differentiation-products required to be classified qualitatively and not quantitatively, since it was only by this means that the natural order could be reflected in a scheme of classification. Classifications based on mineral composition and structure were admittedly imperfect; but they were natural, inasmuch as they sacrificed sharpness of grouping in their attempt to copy the natural order of arrangement. It was in this sense that the quantitative-chemical system was rightly stigmatized as unnatural when compared with mineral-textural systems, since it insisted upon the essentiality of 'sharp artificial boundaries' which did not exist in Nature. The chemical composition of an igneous rock, which the Quantitative System treated as the most fundamental character, was less fundamental than mineral composition. The chemical composition of any given few grams of a holocrystalline rock was determined by the minerals actually present, and at no period of differentiation could it be truly said that this chemical composition was an inherent feature of the magma. On the other hand, the mineral composition was not determined by the chemical composition of the particular piece of rock analysed, but by that of the magma during the various stages of crystallization. By a development of this argument it could be proved that the natural mineral composition of a rock was more fundamental than its chemical composition or any artificial norm calculated therefrom, and was therefore a sounder basis of classification.

Dr. L. L. FERMOR said that most of the previous speakers had spoken disapprovingly of the Quantitative Classification of igneous rocks. He did not advocate its adoption, but drew attention to one good feature, namely the idea of the norm. In dealing with a rock the speaker found it very helpful to be able to compare one rock with another, not on the basis of their actual mineral composition, nor even of their chemical analyses, but preferably by converting the

[Mica might also have been mentioned in this connexion.—*J. W. E.*]

506 THE NATURAL CLASSIFICATION OF IGNEOUS ROCKS. [Aug. 1910.

chemical analyses into the standard mineralogical composition known as the norm: thus comparing the rocks mineralogically, but yet without reference to their actual mineral composition and physical structures, which after all were in a way accidental features dependent not merely on the original composition of the magma, but on its treatment during and after solidification.

Dr. TEALL thanked the Society on behalf of his friend the Author for the way in which they had received the paper. There appeared to be general agreement on the main subject of the paper, for the criticisms had been almost entirely directed to the Quantitative System of classification. Much of this criticism seemed to him to be rather wide of the mark. Was the system of real utility as aiding thought? This, after all, was the important question, and on the answer that would ultimately be given to it depended the fate of the classification.