THE BASIC IGNEOUS ROCKS of GREAT BRITAIN.

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IGNEOUS ROCKS.

The igneous rocks are those that have been formed by the consolidation of molten material derived from the interior of the earth.

There are reasons for believing that the temperature of the interior of the earth is very high, high enough, indeed, to melt the most refractory rock known to us. Amongst the reasons, the following may be mentioned:-

(1) The Existence of Volcanoes. - In many regions of earth's surface, openings exist from which steam, hot vapours, ashes, and molten lavas are from time to time emitted. The existence of these widely separated volcanoes is only explicable by the assumption of a very high internal heat. The fact is brought home to our mind more clearly when one adds to the number of existing active volcanoes, the remains of extinct ones,

from which, in early geological periods, enormous quantities of molten material were poured out. The remnants of these enormous sheets of igneous rocks are met with nearly all over the globe, When we consider that they have all risen from below, as if from a common reservoir, we are inclined to admit of the existence of a very high temperature within the earth.

(2) Hot Springs. - In regions where volcanic activity has ceased, evidence of internal heat is still manifested in hot springs and geysers. From the temperature of the discharged water they appear to maintain a high temperature for many centuries.

Hot springs are found even in regions many miles away from existing volcanoes. The hot spring of Bath (temp. 120° F) in England is 900 miles from Icelandic Volcanoes, and about 1100 miles from those of

Italy and Sicily.

(3) Borings. - As the crust of the earth is penetrated below the zones of seasonal changes by wells, mines, and borings, the temperature is almost invariably found to rise. The rate of rise is, however, far from uniform. From the report of the British Association for Advancement of Science, it appears that the range varies from 1° F. in less than 20 feet to 1° F. in 130 feet, with an average of 1° F. in 50 to 60 feet, which has usually been taken as representative.

The question of the ultimate origin of igneous action, including the source of the magmas and the nature of the motive power, is inseparably connected with other questions, e.g. the origin of our planet and the present physical and thermal conditions of its interior parts, - questions which are still undecided. This branch of speculative science, which is known as Cosmogony, has got too many diverse theories impossible to reconcile. It is only possible to touch them briefly here. Laplace's Nebular Hypothesis is seemingly beset with insuperable difficulties; no less precarious is the condition of Meteoric Hypothesis. The planetesimal Theory has as yet scarcely emerged from the tentative stage. (Harker. Igneous Rocks, p. 4).

As regards the present physical condition most diverse theories still find champions. The question has been attacked both by geologists and physicists, with the result that most uncompromising theories have been put forward. According to Lord Kelvin the globe was a solid, having rigidity nearly as that of steel. Fisher has got a slightly different view by assuming a fluid substratum over a solid nucleus. On the other hand Arrhenius advocates the view that the greater part of the globe is gaseous, passing through a liquid layer to a solid crust some forty miles thick. It may be mentioned that all the foregoing theories, though very diverse in character, are dependent more or less on the assumption of Nebular Hypothesis. On the Planetesimal Hypothesis as developed by Chamberlain, "the globe may be supposed practically solid but with liquid tongues and threads emanating from places of local fusion in the middle zone and work their way outward".

Whether the portion of the earth immediately beneath the crust is occupied by rock in the molten condition, or by solid material at a sufficient high temperature to become liquid under a diminished pressure, it is clear that if by one means or another the external pressure be overcome, liquid magma will move in the direction of least resistance. According to the nature of the resistances offered by the surrounding mass, the molten material will pierce the solid crust of the earth to a greater or less distance; it may reach the surface and give rise to the phenomenon known as "Volcanic Action", or it may consolidate in large masses at considerable depths forming rocks which are termed "plutonic, deep seated, or abyssal", while the former are known as "Volcanic". Connecting the volcanic rocks with the parent magma are necks and pipes or dykes. Besides, the plutonic masses send off tongues and apophyses to the surrounding rocks which never find outlet but consolidate between strata as intrusive sheets. The term "Hypabyssal" is, therefore, used to embrace this third group of igneous rocks forming the connecting link between plutonic and volcanic rocks. Plutonic and hypabyssal rocks are "intrusive", while the volcanic rocks are "extrusive".

Definition of the chief forms in which plutonic rocks occur:-

(a) Stock or Boss: An irregularly shaped intrusive mass which cuts across the structure of the invaded formation. The contacts are often vertical or highly inclined, and there is no visible floor on which the erupted material rests. (Hatch).

(b) Dome: A circular or oval shaped granite mass exposed amongst sedimentary rocks with its sides dipping underneath the surrounding rocks at a gentle angle.

(c) Dykes: Are generally formed by the injection of magma in narrow and nearly vertical fissures. They have approximately constant width, - small in comparison with the longitudinal and vertical extension. Some dykes represent conduits of sills, others are self-contained with no ulterior end.

Sill: Is characterised by a wide lateral extension as compared with its vertical thickness. Its regularity of behaviour in following a defined bedding plane is often very remarkable, and the thickness is sometimes very uniform for long distances. One-half of the 'basaltic plateaux' of Ulster and Inner Hebrides is made of great successions of dolerite sills, varying in thickness from a few feet to 100 feet or more, and individual sills can be followed for many miles.

Laccolite: The term was first introduced by Gilbert in describing an intrusive mass having a flat base and a dome-shaped upper surface. (Report on the Geology of Henry Mts. 1880). It has more restricted areal extension than a sill. Both slope and thin out towards the edge, but in the case of a laccolite the thinning out is more rapid. It is generally formed at a great depth and consequently at an enormous pressure.

IGNEOUS ACTION.

A glance at the geological map of any extensive area makes it apparent that there is a general correspondence as regards both time and space of igneous action with important movements of the earth's crust. In some cases igneous action seems to be the immediate cause of 'folding' and 'faulting'; in others it is consequence rather than the cause of displacement of solid crust. Whether one is the cause or the effect of the other, it is immaterial to discuss. Taking, however, a broader view and overlooking this distinction, we may say that the two sets of phenomena - igneous action and crust movement, - are co-ordinate effects of the same ultimate cause. The strains set up in the crust of the globe, 'cosmic and regional', develop local stresses which may, ultimately, overcome the limit of resistance. "That limit passed, the stresses must find relief in a readjustment of the crust", and such readjustment may be effected by relative displacements of solid rock or of fluid magma, or, more generally, of both together. Thus the two sets of phenomena, though not actually coincident, are in some degree complementary to one another. Accordingly we find that igneous action has prevailed in those regions of the earth's crust which have also been the theatre of great elevation and depression, folding, faulting, and overthrusting of the solid crust

The readjustment of the crust may take place either (a) in a vertical, or (b) in a horizontal direction, - the former forming 'plateau' and the latter 'mountains'. Corresponding to these two crustal movements are two types of volcanic eruptions, - the "fissure" type generally accompanies the vertical movements, and the "central" type is limited to the horizontal movements. Similarly we find different forms of intrusive bodies related to different types of crust movement. Under each of the two categories mentioned before, (e.g. "plateau and mountain areas") are comprised intrusions of widely different habits. According to the diverse postures assumed by the intruded rock bodies and their attitude towards the "country rock", they may be distinguished as (a) concordant and (b) transgressive. "In the one case the intruded magma has been guided by surfaces of structural weakness, such as particular bedding planes, in the rocks invaded. In the second case the intrusions have systematically broken across the bedding or other directional surfaces of the country rock". (Harker. Igneous Rock. pp. 61-62). So the intrusive bodies may be conveniently divided as follows:-

	Plateau District.		Mountain District.
Concordant.	Sill laccolite bysmalite.	Concordant.	phacolite.
Transgressive.	dyke.	Transgressive.	sheet. dyke.

The dynamical aspect of igneous action, as has been mentioned before, may be distinguished as "intrusive" and "extrusive", according as the displaced magma is raised from a lower to a higher level within the earth's crust or brought to the surface and poured forth as sub-aerial or subaqueous lavas. It is now generally interpreted that these actions represent the different phases of intrusion: the one characterised by large bodies of plutonic mass, the other by the injection of numerous smaller bodies such as dykes, sills, laccolites etc. Thus we have three distinct phases of igneous action, namely, (1) volcanic extrusions, (2) large plutonic intrusions, and (3) minor intrusions constituting a regular cycle, in which the several phases follow in the fixed order.

MAGMATIC DIFFERENTIATION.

The most fundamental problem of modern petrology, that of the origin of the great diversity of rock types actually found, has engaged the attention of numerous writers. Though attacking the problem from different stand point of view, they all, in general, aim at providing some physical explanation of the derivation of diverse rocks from one parent magma.

The earliest effort in this direction is due to Bunsen, who as early as 1851 pointed out that the varying composition of large series of igneous rocks which he had examined from different parts of the world could be expressed on the assumption that they are due to the mixture, in varying proportions, of two distinct magmas, which he designated by the terms "normal-trachytic", and "normal-pyroxenic". In 1857 Durocher advanced a theory very similar to Bunsen's. According to him the igneous products of all ages have been derived from "two magmas which co-exist beneath the solid crust of the globe and occupy there each a definite position". The terms acid and basis were given to these two magmas, and their average compositions were supposed to be as follows:-

	Acid.	Basic.
SiO_2	71.0	51.5
Al_2O_3	16.0	16.0
FeO	2.5	13.0
CaO	1.0	8.0
MgO	1.0	6.0
K_2O	4.5	1.0
Na_2O	2.5	3.0
Sp. gr. of crystalline rock	2.65	2.95
-do- glass	2.40	2.72

Rocks of intermediate composition were supposed to be due to the intermixture of the two magmas. Summarily, then, we meet in nature two extreme types; the one characterised by a low percentage of silica, high percentages of lime, iron and magnesia; a low percentage of alkalies, and an excess of soda over potash: the other by high percentage of silica, low percentages of lime, iron and magnesia; a high percentage of alkalies, and an excess of potash over soda. Between these two extremes we have every possible gradation. (Bunsen's Law).

The effect of crystallization in modifying the composition of an igneous magma is immense. If, for instance, crystallization is allowed to proceed to a certain extent ina magma of "andesitic" composition the crystals when separated are found to have a basic and the remaining liquid magma an acid composition. It seems quite possible, then, that the variations in the composition of the igneous rocks which are expressed by Bunsen's Law, may be due to differentiation produced in an originally homogeneous magma in consequence of progressive crystallization.

The evidence for magmatic differentiation, which seemed sufficient to the earlier petrologists, has been enormously strengthened by increasing knowledge of the distribution and mutual relations of different kinds of igneous rocks. The variation apparent in differences of composition between rocks, however intimately associated, must be regarded as representing distinct intrusions (or extrusions) of magma. But in addition there are many cases in which a rock-body, representing a single intrusion of magma, shows considerable variation in different parts of its mass. While the former kind of variation is probably due to differentiation prior to intrusion, the latter, at least, is attributable to differentiation subsequent to intrusions, and may be said as effected "in place". It does not necessarily imply, however, two kinds of differentiation as regards the mechanism of the processes concerned. Harker is of opinion that "the variation observed in a single igneous rock-body is due to processes of diffusion closely bound up with progressive crystallization". (Igneous Rocks. p 311). That similar action takes place also in the inter-crustal magma-reservoirs may be assumed from the fact that these reservoirs must be situated in a zone of earth's crust where solid and liquid rock are in approximate equilibrium, and where consequently crystallization or fusion will readily be brought about in response to changes of pressure or temperature It may be noticed here that the foregoing theory of Harker is based on Vogt's conclusion that natural rock-magmas are in general freely miscible with one another in any proportions at all temperatures at which they remain fluid. The most importamt exception is the case of the sulphides, which appear to have only a limited degree of miscibility with slicates in the molten state. But there are some petrologists who are of opinion of only a limited miscibility between two portions of the magma, with the result that masses differing in specific gravity separate out in layers. Many theories, based upon this principle, have been put forward as explanations of the phenomena of magmatic differentiation. Backstrom, for instance, would "give to liquation and not diffusion its place as the working hypothesis, upon which the theory of differentiation is to be constructed". Rosenbuch's Kern hypothesis, based also on the assumption of limited miscibility, is an attempt to classify igneous rocks on the basis of magmatic differentiation. The process involved is a sort of "spontaneous division" of homogeneous magma into partial magmas characterised by a "certain chemical individuality and having only a limited mutual solubility". Soret had proved that in aqueous solution of a salt, different parts of which are maintained at different temperatures, there is a stronger concentration of the salt in the cooler region. Based on this principle, some petrologists have attributed a leading part in the differentiation of a still fluid magma to 'difference of temperature' between different parts of the magma basin or again between the central and the marginal parts of an intruded body of magma. A consideration of this principle, from the quantitative point of view, shows, however, that the result is of very trifling importance. (Harker. Igneous Rocks. p. 317).

The best explanation of differentiation "in place" is afforded by the process which has been very appropriately styled by Becker as "fractional crystallization". By means of this process differentiation is brought about concurrently with, and as a consequence of, the progress of crystallization in a rock magma. It is to be noted, in the first place, that the crystallization of any constituent from a mixed solution necessarily implies differentiation. As, for instance, when a crystal proceeds to form in a magma, its growth is fed by diffusion-currents, which maintain a certain degree of supersaturation in the immediate vicinity of the crystal, carrying the necessary constituents to it and foreign substances away. As a result of this we may find a certain part of the rock, where the crystallization has been localised, crowded with one sort of crystal, and other parts marked by the paucity of its presence. Between these two extremes, however, there is a continual gradation of mixtures. Theoretically there is no limit to such a process of differentiation. In the extreme case it is even conceivable that the requisite conditions being maintained, there may be formed a rock consisting wholly of one mineral, the remaining fluid magma being totally deprived of that constituent. The requisite conditions are that (1) the earlier minerals shall separate successively out according to their decreasing basicity, (Rosenbuch's Law), (2) one part of the body of magma shall be constantly at a lower temperature than the rest.

"It is quite reasonable to suppose that the process of fractional crystallization, which appears to be of prime importance in the differentiation in place of intruded rock magmas, plays a part likewise in that intratelluric differentiation by which these magmas had their origin. Its most obvious application is to a series of rocks which are composed of the same minerals in different proportions.

Supposing, now, that differentiation takes place in accordance with the principle formulated above, let us enumerate the effects that we may expect to meet with on the resulting rock when a mass of molten material of sufficiently large size - so that no rapid chilling takes place, - is intruded in some pre-existing rock mass. Assuming that there is sufficient initial difference in temperature between the intruded magma and the surrounding rock, differentiation will take place, and as a consequence there will be variation of varieties. Since the differentiation is conducted with reference to the surface of contact, the variation will be developed in an orderly manner, - with bilateral symmetry in a dyke or sheet, and with a concentric arrangement in a boss or laccolite.

Now, let us compare this result with what we find in nature. An examination of sills, dykes, or laccolite all show a basic marginal modification and a gradual increase of acidity towards the centre of the mass. Of course the extent of such a differentiation will be governed by the fluidity and viscosity of the intruded magma. On account of the greater fluidity of basic magma, differentiation will be more pronounced in gabbro than in nepheline-syenite.

PETROGRAPHICAL PROVINCES.

We have seen that, as the result of differentiation, the assemblage of rocks in any given area of earth's surface may range from quite basic to very acid type. In spite of this difference, they may have some chemical characters in common which place them in a definite series. As for example, Iddings in 1892, pointed out that rocks relatively rich in alkalies are found along the eastern side of the Rocky Mountains and Andes, and further east in Canada, the United States, and Brazil, while a sub-alkali group is developed throughout the Great Basin of the Western States, on the Pacific Coast into Mexico and Central America, and along the whole extent of the Andes.

Similar prevalence of one type or the other, in smaller areas, first led Prof. Judd to his conception of "Petrographical Provinces". It leads at once to the hypothesis that igneous rocks of one province owe their resemblance to the community of origin. Such presumed genetic relationship or "consanguinity" as Iddings calls it, has been the keynote of many petrologists in their effort to explain the origin of the diverse associated rock types by process of differentiation from a common stock magma.

That the two fold division noted by Iddings has a very wide range of application is proved by Harker in his attempt to show "the very general correspondence of the areas of the alkali and sub-alkali groups respectively with the areas of the

Atlantic and Pacific types of coast line as defined by Suess." The one type is found around the Atlantic and part of the Indian Ocean and in the Polar basins, the other, generally speaking, around the Pacific.

The two types are characterised by minerals which have been classified by Harker as follows:-

Alkali Group. (Atlantic).	Sub-alkali Group (Pacific).
Alkali-felspar form a large proportion of the more acid and intermediate rocks, and occur in many rocks of low acidity.	Alkali-felspars not abundant except in the more acid rocks, and wanting in the basic; soda -lime felspars abundant.
Microperthetic and Crypto-perthetic intergrowths frequent.	Zonary ~~boundary~~ banding of felspar frequent.
Felspathoid minerals often found (leucite, nepheline, sodalite, primary analcime; also melitite).	Felspathoid minerals not found.
Quartz confined to more acid rocks.	Quartz not only in acid rocks, but also in many intermediate ones.
Pyroxenes and Amphiboles often include soda-bearing kinds.	Pyroxenes represented by augite, diaopside, and the rhombic group; amphiboles by common hornblende.
Micas and garents are of common occurrence.	Micas not common except in the more acid rocks.

CLASSIFICATION OF ROCKS.

To a student of geology of present day, nothing is so disconcerting as the subject of classification of rocks. It is tolerably easy for him to describe a rock and determine its chemical and mineralogical constituents, but it is hardly possible to assign a position to it in a satisfactory system of classification. The difficulty not only arises from the nature of the subject, but also from the disagreement which at present exists amongst the petrographers even as regards the first principles on which the classification should be based.

One of the earliest attempts to classify igneous rocks was due to the continental petrographers, who made the geological age as the basis of the classification. But Allport and others later on proved, beyond doubt, that rocks of many ages are identical in their material qualities, so classification on this basis is no longer satisfactory nor acceptable. The inherent characters of igneous rocks have always been the basis of classification. Of these the chemical and mineralogical composition, texture, and structure, are the most important. Structure and texture are now known to depend on the variable conditions attending the consolidation of magmas. Classified on this basis rocks having the same, or very similar composition, e.g. granite and rhyolite, are put in widely separated groups. Consequently they can no longer be given the prominent rôle hitherto assigned to them.

Ideally it would be possible to make chemical composition a basis of classification of igneous rock, as this is their most fundamental characteristic. The absence of stochiometric proportions amongst the chemical components, however, render this treatment difficult. This difficulty is further enhanced by the presence of an intricate inter-relationship amongst the components. These facts show that any subdivision on purely chemical basis is hardly possible.

A classification based on purely mineralogical characters is equally beset with difficulty. The existence of vitreous and hemicrystalline rocks make it impracticable. The task would not have been much lightened even if all the rocks were holocrystalline, for a given magma may crystallize in different mineral combinations.

So it is evident that neither of the above can alone or independently be applied as a basis of satisfactory classification. And since the minerals are easily determinable optically, it seems convenient to retain the mineralogical treatment of the rocks. The original minerals of a holocrystalline rock may be considered as a fair representative of the original magma. Again, the original magma of a hemicrystalline or vitreous rock is only truly represented by its chemical composition. So considering the entire range of igneous rocks as a whole, a satisfactory classification seems possible only on the combined "chemical and mineralogical"properties of the rocks.

A few years ago a new system of classification was introduced by some American petrographers. (Classification of Igneous Rocks by Washington and others, 1903). The system is based principally on the quantative analysis of the rocks.

"Whether vitreous or crystalline, all igneous rocks may be correlated by considering what mineral combinations may be developed from their magmas if crystallized. But since several mineral combinations are possible for most magmas, it is advisable to select one of these combinations as the standard of comparison, and for uniformity and simplicity it is necessary to select the same one for all rocks having like chemical composition. This may be termed the "standard mineral composition", which may or may not correspond to the actual mineral composition." (Classification of Igneous Rocks p. 113).

The scheme first starts by grouping the important rock forming minerals into five groups as "distinguished by Chemical Characters", and also by associations in the rocks. Rock forming minerals are divided by the Authors into two groups, - the 'salic' and the 'femic'. The 'salic' group contains minerals which have a siliceous and aluminous character. The 'femic' group is characterised by ferro-magnesian minerals.

The mineralogical classification of a rock is anything but qualitative, and as a natural consequence, in all classifications based on mineral characters, quantitative considerations have been almost disregarded. As long as the minerals which form part of the definition of a rock are present, they may vary in amount indefinitely without, in most cases, affecting its nomenclature or its place in classification.

It is with the object of remedying this defect that the Authors have devoted themselves to the introduction of a new system. They recognise that by far the most important character of an igneous rock is its chemical composition. "The chemical composition of the rock is its most fundamental character, being a quality inherent in the magma before its solidification, and is therefore of the greatest importance in its correlation with other rocks".

"All rocks of like chemical composition should be classed together, and degrees of similarity should be expressed by the relative positions and values of the systematic divisions of the classification".

"The mineral and textural characters, being dependent largely on external conditions attending rock consolidation, are to be regarded as subsiding importance in classification, but should receive due recognition in the system".

As, however, magmas, having the same chemical composition, may crystallize out in different mineral aggregates, the Authors have devised a method of calculating from the chemical analysis of a rock, a standard mineral composition called the 'norm', which might, in some cases, practically coincide with the actual mineral composition or 'mode', but, as a rule, differ widely from it.

OUTLINE OF THE SYSTEM.

The subdivisions proposed by the Authors are:-

Class,	Sub-class.
Order,	Sub-order.
Rang,	Sub-rang.
Grad,	Sub-grad.

The division into classes and orders is based on gravimetric calculation; that is, it is determined by the ratio of the total weights of the groups of minerals on which the classification depends; but in forming the smaller divisions, - the rangs and sub-rangs, - it is the molecular proportion of a certain chemical constituent that is considered.

(1) The Chemical Composition. - The starting point on this new system is the chemical composition of the rock,

which may be ascertained either from a chemical analysis, or calculated from a quantitative estimation of the minerals present.

(2) Norm. - The chemical composition having been determined, the calculation of 'norm' is proceeded with. By dividing the percentage of the different chemical constituents by their molecular weights, the molecular proportions are obtained. The molecules are then distributed according to fixed rules to form the minerals of the 'norm'. Minerals, whose composition is too complex, are either dissociated into less complex ones or are entirely excluded.

The method of allotment of the molecules is intended to express, as far as possible, the natural affinities and preferences among the chemical constituents of igneous rocks.

The Classes. - The primary divisions, into which igneous rocks are classified, are dependent on the relative proportions of the salic and femic mineral groups, as calculated in the standard mineral composition of each magma. There are five classes based on the following proportions:-

Class	1.	$\frac{Sal}{fem} > \frac{7}{1}$,	persalic.
"	11.	$\frac{sal}{fem} < \frac{7}{1} > \frac{5}{3}$,	dosalic.
"	111	$\frac{sal}{fem} < \frac{5}{3} > \frac{3}{5}$,	salfemic.
"	1V.	$\frac{sal}{fem} < \frac{3}{5} > \frac{1}{7}$,	dofemic.
"	V.	$\frac{sal}{fem} < \frac{1}{7}$,	perfamic.

Sub-class. This division is based on certain broad chemical distinctions in the salic and femic groups, which make it possible to divide each of them into two parts:-

Salic Group.	Part 1. - Quartz (Q) Felspars (F) and felspathoids (L).
	" 11. - Zircon (Z) Corrundum (C)
Femic Group.	Part 1. - Pyroxenes (P) Olivine (O) Magnetite (M)
	" 11. - Apatite (A).

Sub-classes in Class 1, 11, and 111, are made on a fine fold basis, by considering the relative proportions of the two parts of the salic group just described. $\left(\frac{Q\ F\ L}{C\ Z}\right)$. In classes 1V. and V. sub-classes are formed on the proportions of the two parts of the femic group. $\left(\frac{P\ O\ M}{A}\right)$.

(4) Orders. Each of the five classes is again divided into orders. The subdivision into orders of the first three classes depends on the proportion of

felspars to quartz, on the one hand, and felspathoids ('Lenad's') on the other. As is well known, these do not occur together. There are nine orders in each class:-

Order 1.	$\frac{Q}{F} > \frac{7}{1}$,	Quartz extreme,	Perquaric.
" 2.	$\frac{Q}{F} < \frac{7}{1} > \frac{5}{3}$,		doquaric.
" 3.	$\frac{Q}{F} < \frac{5}{3} > \frac{3}{5}$,		quarfelic.
" 4.	$\frac{Q}{F} < \frac{3}{5} > \frac{1}{7}$,		quardofelic.
" 5.	$\frac{Q}{F} < \frac{1}{7}$,	felspar extreme,	perfelic.
" 6.	$\frac{L}{F} < \frac{3}{5} > \frac{1}{7}$,		lendofelic.
" 7.	$\frac{L}{F} < \frac{5}{3} > \frac{3}{5}$,		lenfelic.
" 8.	$\frac{L}{F} < \frac{7}{1} > \frac{5}{3}$,		dolenic.
" 9.	$\frac{L}{F} < \frac{7}{1}$,	lenad extreme,	perlenic.

The remaining two classes are each divided into five orders according to the proportion of femic silicates to non-silicates.

Femic Group
- 1 - Silicates.
  - (a) Pyroxenes etc. (P)
  - (b) Olivine " (O)
- 2 - non-silicates - Magnetite " (M)

Order 1.	$\frac{P + O}{M} < \frac{7}{1}$,	perpolic.
" 2.	$\frac{P + O}{M} < \frac{7}{1} > \frac{5}{3}$	dopolic.
" 3.	$\frac{P + O}{M} < \frac{5}{3} > \frac{3}{5}$	polmitic.
" 4.	$\frac{P + O}{M} < \frac{3}{5} > \frac{1}{7}$,	domitic.
" 5.	$\frac{P + O}{M} < \frac{1}{7}$.	permitic.

(5) Rangs and Subrangs. Each of the orders of the first three classes is subdivided into five minor groups, known as rangs, according to the molecular proportion in the salic minerals of the alkalies to the lime. $\frac{K_2O' + Na_2O'}{CaO}$

Of classes IV. and V. rangs are formed upon a five fold basis of comparison of the two sets of chemical constituents, namely, MgO, FeO, CaO″, and the alkalies, K_2O'', Na_2O''. $\left\{ \frac{(Mg + Fe)O + CaO''}{K_2O'' + Na_2O''} \right\}$

Each of the rangs is again split up in an exactly similar fashion into five subrangs, according to molecular proportion of the bases in the femic minerals.

(6) Grads. Are based on the proportions of the standard minerals of the subordinate femic and salic groups in Classes II. and IV. and of the femic group in Class III.

Subgrads are formed on the general chemical character of the bases of the minerals employed to form Grads, and bear the same relation to the latter that Rangs bear to orders.

The 'quantitative classification' is considered by Harker as a retrograde movement, for here the artificial element is applied to the complete exclusion of the natural. The division of group from group by lines drawn at arithmetical intervals, can correspond to nothing that has occurred in the evolution and differentiation of igneous rocks. These purely arbitrary boundaries would in many cases separate a common and simple rock type into two or three portions with different names and positions in the classifications.

The Author's object is that "all rocks of like chemical composition" should be classed together. Throughout the classification, both in the large and small divisions, the extent of variation of the principal oxides is considerable. As a consequence we find, as has been pointed out by Harker, in the same subrang, rocks like rhyolites, trachytes, dacites, and hypersthene-andesites all packed together. "It would be difficult to say wherein these resemble one another and differ collectively from the assemblage placed in any of the neighbouring compartments of the scheme". (Igneous Rocks. pp. 363-364).

The mineralogical composition employed in the quantitative classification is, as has already been pointed out, not the real one, but an ideal one, called the 'norm'. Starting from a list of standard minerals which corresponds only very imperfectly with the actual rock forming constituents, the scheme is built up without any consideration of how rocks, genetically related, will fit in the rows of compartments so connected.

The 'quantitative classification' has not found many supporters amongst the British Petrographers, although it is generally recognised by petrographers across the Atlantic. The least that can be said against this classification is that it is not a natural classification, and so can show but very poorly the genetic relationship which undeniably exists between different igneous rocks.

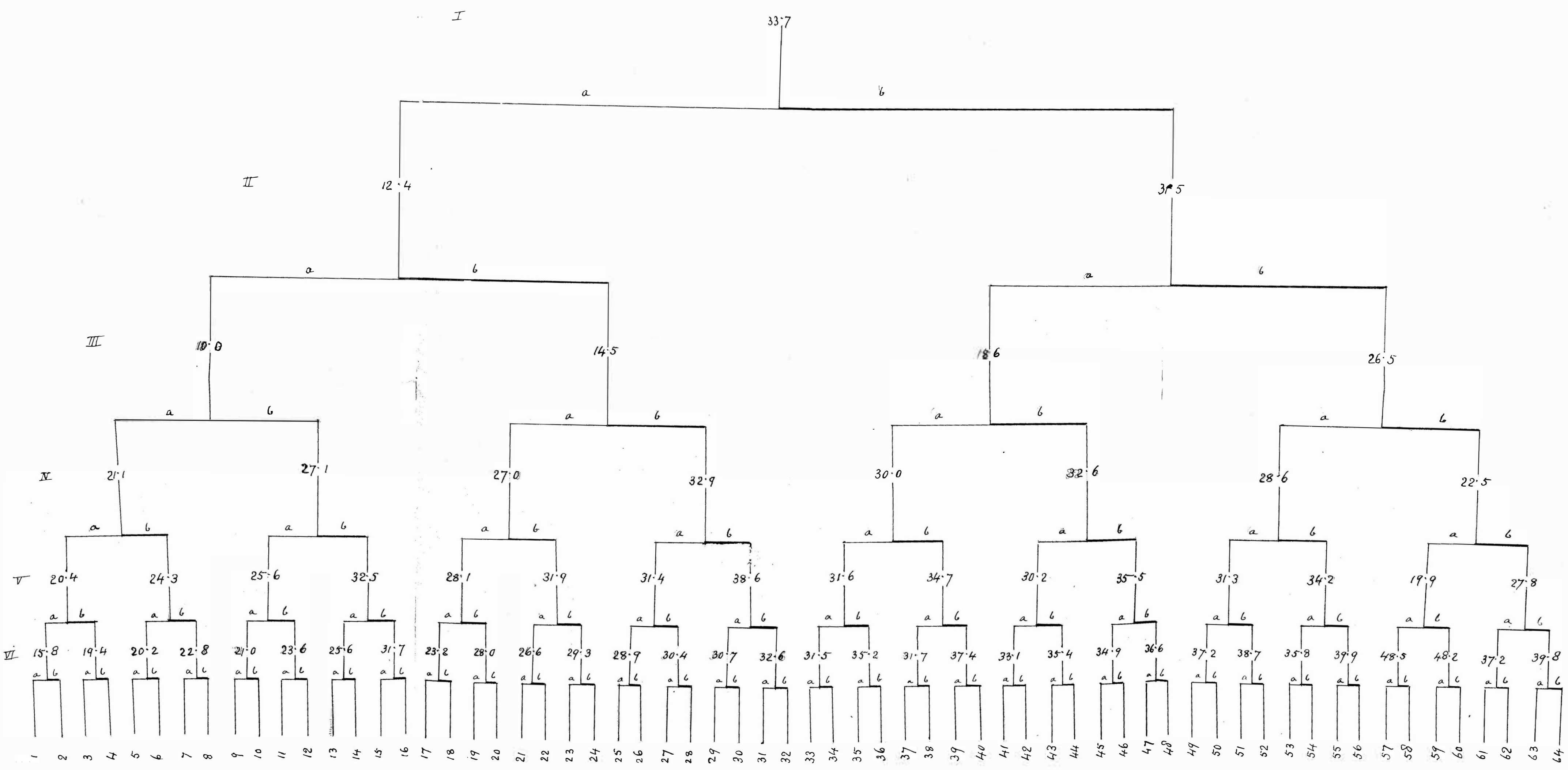
The Method of Classification. First the following quantities of oxides derived from the general average composition are added together:-

(1) $Al_2O_3 + (Fe_2O_3 + FeO) + MgO + CaO$,

the result being found - 33.7

All the rocks are now separated into two groups, those which "yield individually for the same bases a sum smaller than 33.7, and those which yield a sum larger than 33.7". (Pro: Royal Soc. Edin. Vol. XXVIII. Part II. No. 7.) All the former are marked (a), and the latter (b). Thus the total number of rocks are practically divided into two equal halves.

For each of these two sets (a) and (b) the average totals of the following bases are now calculated:-



I
33·7
II
12·4
31·5
III
10·0
14·5
18·6
26·5
IV
21·1
27·1
27·0
32·9
30·0
32·6
28·6
22·5
V
20·4
24·3
25·6
32·5
28·1
31·9
31·4
38·6
31·6
34·7
30·2
35·5
31·3
34·2
19·9
27·8
VI
15·8
19·4
20·2
22·8
21·0
23·6
25·6
31·7
23·2
28·0
26·6
29·3
28·9
30·4
30·7
32·6
31·5
35·2
31·7
37·4
33·1
35·4
34·9
36·6
37·2
38·7
35·8
39·9
48·5
48·2
37·2
39·8

(2) $(Fe_2O_3 + FeO) + MgO + CaO + NaO$

The results are found to be respectively 12.4 and 31.5. These figures are now used in subdividing the group (a) and the group (b) in the same way as in the first case.

Thus the total number of rocks are divided into four sets:-

(a) (a)
(a) (b)
(b) (a)
(b) (b)

The same process is successively repeated by means of the following totals:-

(3) $MgO + CaO + Na_2O + K_2O$

(4) $CaO + Na_2O + K_2O + Al_2O_3$

(5) $Na_2O + K_2O + Al_2O_3 + (Fe_2O_3 + FeO)$

(6) $K_2O + Al_2O_3 + (Fe_2O_3 + FeO) + MgO$.

Thus finally 64 groups are obtained in which the rocks are divided. The respective constants are recorded in the table. The whole of the 1,000 rocks have been arranged by the Author in proper groups. Any other igneous rock, not included in the list of 1,000 rocks, may be arranged under its proper group by reference to the table and simple calculation.

It will be noted that the method adopted by the Author is based purely on quantitative analysis of rocks; the object of classification is a simple mechanical one.

I have the privilege of knowing the Author personally. Not satisfied with the result attained by the method mentioned, Dr. Warth has devised another one which is in the course of preparation. The new method materially differs from the old one, in as much as it is dependent on the molecular proportions of the chemical constituents. Added to this, the new system entails a slightly different order in which the different sets of bases are taken in consideration. They are arranged according to their valency in a descending order. As in the old system only four bases are taken at a time.

The result attained by this improved method is decidedly more satisfactory

BASIC IGNEOUS ROCKS.

In the classification, it has been noted that basis igneous rocks have silica contents below 52%. This low silica percentage plays an important part in modifying the mineral contents, and, thereby, the general character of the rocks.

Rock magmas are, without exception, silicate magmas; that is, they consist of silica together with the bases iron, alumina, lime, magnesia, potash, and soda. If the silica is in excess of the bases, the solidified rock contains free silica or quartz; such rocks are said to be "acid". If, on the other hand, the silica percentage is low, the rock is said to be "basis".

With regard to the mineralogical composition of igneous rocks, the acid rocks are characterized by the presence of silica or quartz in greater or less abundance, together with a dominant alkali-felspar. In the basic group, however, quartz is absent, and the alkali-felspar nearly so. They are chiefly composed of basic lime-bearing felspar, ferromagnesian minerals, and iron ores. Again, even in ferromagnesian minerals, some favour one group in preference to the other. As, for example, olivine is practically restricted to the basic group. Of angite and hornblende, the former generally favours the basic and the latter the acid group.

Owing to the predominance of siliceous and alumino-alkaline minerals, the acid rocks are generally of a light colour. The lowness of silica and the presence and predominance of ferromagnesian minerals and iron ores over the alumino-alkaline minerals, give the basic rocks a dark colour.

The proportion of silica present also greatly influences the crystallization of a magma. Acid magmas crystallize with more difficulty than basic ones, consequently rhyolites (acid glasses) are common and basic glass (Tachylites) comparatively rare.

Laws, Governing the Formation of Minerals in a Solidifying magma.

An igneous magma may be regarded as a mutual solution of the silicates, that build up the complex minerals of the igneous rocks. The laws established by chemists, as regards the separation of salts from supersaturated solutions, are therefore applicable in our case. The law, when thus applied, is defined by Hatch thus:- "Crystals tend to form in a magma, when it becomes sufficiently supersaturated with any definite compound". The gradual fall of temperature causes successive supersaturation with different compounds; which would, therefore, separate out in the order of their solubility. This is, however, modified by the relative proportion or the mass of the substance and the chemical affinity of the bases present as silicates. By way of illustration, Harker quotes an example from his observations in the Isb. of Rum. In a series of rocks, composed essentially of olivine and anorthite, the olivine appears to have crystallized out first when the rock is rich in that mineral, while in varieties rich in felspar the reverse holds good.

Vogt's researches on slags prove that, when two minerals in mutual solution are in 'entectic' proportion, they will make an intimate mixture as they crystallize out. Whichever mineral is in excess of entectic proportion will crystallize out first.

<u>The effect of pressure.</u> Sorby has shewn that the

solubility of salts, which increase in volume as they pass into solution, is lowered by pressure. The rock forming silicates conform to this law. Consequently a magma, which at a certain temperature and pressure is on the point of crystallizing, will, if the pressure is relieved, remain in the liquid state until, by the fall of temperature, the proper state of saturation has been reached. This explains the corrosion and resorption of crystals that have formed in a magma prior to extrusion. The relief of pressure lowers the fusing point of the mineral, and a portion of it passes into solution.

lass	Felspathoid Series.	Soda Series.	Potash Series.	Monzonite Series.	Calc-Alkali Series.
PLUTONIC	Nepheline - Gabbro Theralite - p (with or without O) + nep. Covite - O + Nep. Borolanite - O + Pseudoleucite + nep + melanite. Jacupirangite - nep + aug + M + bio Ijolite - nep + aug + mel. Missourite - leu + aug + bio + ol.	Essexite.	Shonkinite.	Kentallenite.	Gabbro - lab + aug. Olivine-gabbro - lab + aug + ol Norite - lab + aug + hyp Olivine-norite - ol + norite. Troctolite - lab + ol Eucrite - anor + aug + ol Allavalite - anor + ol Anorthite - rock.
HYP-ABYSSAL	Undifferentiated. The Mugea-rite - Tache nite family. Differentiated. Minette - ortho + bio Camptonite - p + horn Monchiquite - ol + {aug / horn / bio		Hornblende Pyroxene rock. Pyroxenite. Picrite - ol + aug.	The Mugearite - Tachenite family	Dolerite - lab + aug Olivine - dolerite - ol + dolerite Hypersthene " - hyp + doler Hornblende " - horn + doler Quartz " - Qu + dol Mica " - Bio + dol
VOLCANIC	Alkali Basalts :- Tephrite - P + {nep / or / leu} + aug Basanite - p + {nep / or / leu} + aug + ol			Ciminite	Basalt - pl + aug. Olivine-basalt - ol + Basalt. Hornblende - Horn + Basalt Tachylite.

	1	11.	111.	1V.	V.	V1.	V11.	V111
SiO_2	51.15	42.22	42.51	50.08	48.13	47.88	40.32	36.15
Al_2O_3	15.91	10.62	12.85	18.87	18.44	13.34	9~~0~~.46	15.18
Fe_2O_3	4.63	4.74	2.67	3.48	3.41	4.09	4.75	4.87
Fe O	3.72	6.18	7.52	3.49	4.30	4.24	7.48	9.11
Mg O	4.14	8.68	12.00	2.14	3.06	7.01	18.12	13.63
Ca O	7.68	14.80	11.83	6.70	5.89	9.32	10.55	11.40
Na_2O	1.92	2.46	2.75	4.10	8.00	3.51	2.62	2.42
K_2O	5.97	1.41	2.15	4.58	3.80	5.00	1.10	1.81
H_2O	2.75	1.66	2.96	4.17	1.77	2.10	1.82	2.32
Ti O_2	-	2.49	-	1.39	1.74	0.58	2.66	2.30
CO_2	2.12	3.57	3.46	-	-	-	-	-
Other Constituents.	-	1.59	0.83	1.16	1.30	3.12	1.21	1.24
	99.99	100.42	101.53	100.16	99.84	100.29	100.09	100.43

1. Minette, Leonhardskopf bei Flockenbach, Odenwald. Rosenbasch.

11. Camptonite, dyke at Sailean Sligenach, West Coast of Ardmuchüish- Pollard.

111. Monchiquite, Grainbank, Kirkwall, Orkneys - Dr. Flett.

1V. Tephrite, Mondhalde, Kaiserstuhl, Baden. F. Graeff.

V. Basanite, Mount Inge, Uvalde County, Texas. - Hillebrand.

V1. Nepheline-Basalt, Tom Munn's Hill, " " "

V11. Leucite " Highwood Peak, Highwood Mts. Montana, Prisson.

V111. Melilite " Spiegel River, near Heidelburg, Cape Colony, J. Lewis.

	1 Mugearite	11. Teschenite	111. Teschenite	1V. Teschenite	V. Hornblende	V1. Pyroxenite
SiO_2	49.24	48.18	47.03	45.71	48.04	45.05
Al_2O_3	15.84	11.80	15.36	15.23	7.82	6.50
Fe_2O_3	6.09	9.79	3.38	2.84	2.01	3.83
FeO	7.18	5.90	7.35	6.93	9.32	7.69
MgO	3.02	6.05	5.10	8.11	13.33	12.07
CaO	5.26	7.50	8.47	7.34	13.01	18.66
Na_2O	5.21	3.46	4.32	3.96	0.69	0.94
K_2O	2.10	1.57	3.00	1.31	0.48	0.78
H_2O	2.69	3.20	2.82	6.24	3.07	2.40
TiO_2	1.84	-	2.64	1.64	1.16	2.65
P_2O_5	1.47	0.49	0.73	0.47	-	-
Other Constituents	0.59	0.71	0.47	0.73	2.03	0.31
	100.53	98.65	100.67	100.51	100.96	100.88

1. Mugearite, Druim na Criche, 5 miles S.S.W of Portree, Skye - Pollard. The Tertiary Igneous Rocks of Skye, Mem Geo. Surv. 1904 p.263.

11. Teschenite, Boguschowitz, Silesia. Rosenbusch, Gesteins lehre p.176

111. " Craigleith Island, N. Berwick-Pollard. Summ. of Pro Geo. Surv. 1906. p.74.

1V. " Sill at Blackburn, Bathgate-Pollard. Summ. Prog. Geo. Surv. 1906.

V. Hornblende-pyroxene rock, Maniposa County, California - Hillebrand. Journ of Geo. Vol 1X. 1901 p.509.

	1. Basalt	11. Basalt	111. Basalt	1V. Basalt	V. Basalt
SiO_2	49.54	49.07	46.61	46.01	48.78
Al_2O_3	22.23	19.43	15.22	19.19	15.85
Fe_2O_3	9.55	10.58	3.49	5.91	5.37
FeO	1.12	2.35	7.71	6.75	6.34
MgO	2.80	4.36	8.66	6.81	6.03
CaO	7.19	7.87	10.08	8.68	8.91
Na_2O	4.56	3.31	2.43	3.27	3.18
K_2O	1.81	0.98	0.67	1.20	1.63
H_2O	2.42	2.26	3.17	3.07	1.76
TiO_2	-	-	1.81	-	1.39
P_2O_5	-	-	0.10	-	0.47
MnO	0.08	0.32	0.13	0.19	0.29
	101.30	100.53	100.08	101.08	100.00

1. Carboniferous Olivine-Basalt, Markle Quarry, Garlton Hills, Haddingtonshire. Grant Wilson.

11. Carboniferous Olivine-Basalt, Hailes Castle, Garlton Hills, Haddingtonshire. Grant-Wilson.

111. Tertiary Olivine-Basalt, Allt Fiounfhuachd, Drynoch, Skye. Pollard.

1V. Carboniferous Olivine-Basalt, Garlton Hills. Grant-Wilson.

V. The average of 161 analyses of typical basalts. (Mostly with olivine). R. A. Daly. Journ. Geo. Vol. XV1. 1908.

	1. Picrite	11. Picrite	111. Picrite	1. Dolerite	11. Dolerite	111. Dolerite	1V. Dolerite
SiO_2	46.23	44.73	42.94	51.22	49.53	48.4	47.45
Al_2O_3	6.30	11.89	10.87	14.06	15.05	13.4	14.83
Fe_2O_3	4.30	4.85	3.47	4.32	4.49	4.0	2.47
FeO	7.07	6.61	10.14	8.73	9.07	8.5	14.71
MgO	25.13	10.77	16.32	4.42	4.25	6.5	5.00
CaO	6.08	7.69	9.07	8.33	8.08	8.6	8.87
Na_2O	1.08	2.77	0.90	1.25	1.25	2.1	0.99
K_2O	0.33	0.89	0.15	2.55	3.93	3.1	2.97
H_2O	3.78	7.64	6.09	1.47	2.53	2.2	1.10
TiO_2	-	1.53	-	2.42	1.76	3.1	1.47
Other Constituents	0.33	1.06	-	0.90	0.89	-	0.36
	100.63	100.43	99.95	99.67	100.83	99.9	100.12

1. Picrite, Little Assynt, Scotland. Grant-Wilson.

11. " Sill at Blackburn, Bathgate Hills, Pollard.

111. " Anglesey. J. H. Phillips.

1. Quartz-Dolerite, Whin Sill, Cauldron Snout. Teall.

11. Porphyritic Olivine-Dolerite, Intrusive Sill, Ealaist Canner - Pollard.

111. Dolerite, Clee Hills. J. H. Player.

1V. " North side of Scourie Bay, N. W. Highlands. - Teall.

	1.	11.	111.	1V.	V.	V1.	1.	11.	111.	1V.
Si O_2	46.73	46.99	48.00	44.65	49.70	48.19	48.05	46.39	45.73	42.20
Al_2O_3	10.05	17.94	12.52	13.87	18.45	18.52	15.35	26.34	22.10	17.56
Fe_2O_3	3.53	2.56	8.74	6.06	3.39	4.51	1.86	2.02	0.71	1.20
Fe O	8.20	7.56		2.94	4.32	1.68	7.53	3.15	3.51	6.33
Mg O	9.68	3.22	15.26	5.15	2.32	1.12	12.53	4.82	11.46	20.38
Ca O	13.22	7.85	7.94	9.57	7.91	10.29	11.02	15.29	9.26	9.61
Na_2O	1.81	6.35	5.11	5.67	5.33	5.44	1.26	1.63	2.54	1.11
K_2O	3.76	2.62	2.68	4.49	4.95	8.05	0.19	0.20	0.34	0.11
H_2O	1.24	0.65	1.36	3.06	1.54	3.45	0.60	0.58	4.38	1.19
Ti O_2	0.78	2.92	0.22	0.95	1.33	1.75	0.49	0.26	-	0.09
P_2O_5 & other constituents	1.93	0.94	-	3.52	0.40	-	1.32	0.14	-	0.43
	100.93	99.60	99.83	99.93	99.44	101.00	100.20	100.82	100.03	100.21

(8.74 in column 111. is bracketed for both Fe_2O_3 and FeO.)

1. Shonkinite, Square Bute, Highwood Mts. Montana.
Prisson. Bull. Geo. Soc. Ame. Vol.Vl. 1895

11. Essexite, Salem Neck, Essex County, Mass, - Washington.
Journ. Geo. Vol.Vll. 1899

111. Kentallenite, - Kentallen, near Ballachulish. Argyl.
Teall, Rep. Geo. Surv. 1896.

1V. Theralite (Covite), Gordon's Butte, Crazy Mts. Montana.
Hillebrand, Bull. U.S. Geo. Surv. 1898

V. Covilite, Magnit Cove, Arkansas, - Washington.
Journ. Geo. 1X. 1901.

Vl. Boralanite, Amer Meallan, Loch Brolan, Ross - C. Smith.

1. Eucrite, $\frac{3}{4}$ mile N.E. of summit of Allival, Isle of Rum.
Pollard. Summ of Progress, Geo. Surv. 1903.

11. Olivine-gabbro, cuillin laccolith, West Bank of Sligachan River
Skye. Pollard. Summ of Prog. Geo. Surv. 1899.

111. Troctolite, Coverack, Cornwall. Rosenbuch.

1V. Allivalite, 70 yds. S. of summit of Allival, Rum.
Pollard. Summ. of Prog. Geo. Surv. 1903.

CHARACTERS of the ROCK FORMING MINERALS.

Felspar. Orthoclase is rather rare as a rock-forming mineral of this group. Its presence, in the ordinary basic rocks of Britain, has not been positively determined, although Mr. Waller, both by chemical and microscopical analysis, has proved its occurrence in certain contemporaneous veins in the Rowley Rag Dolerite. This will be dealt with in detail in a later chapter. It will, perhaps, be well to mention here some crucial tests by which its presence can be determined under the microscope, such as, (1) straight extinction in sections giving rectangular outlines. That is in sections of the zone 100:001, and (2) simultaneous extinction in the two halves of a binary twin (carlsbad), when the trace of the face of composition lies parallel with the shorter diagonal of one of the nicols.

Chemical analyses show that potash, in small quantities, is a normal constituent of basic rocks. This fact, however, does not prove the independent existence of potash felspar.

Triclinic Felspars. These may be either primary or secondary, the latter being characteristic of rocks which have undergone metamorphism. The primary felspar may occur as:-

(1) Porphyritic crystals, with more or less definite form, or as fragments of such crystals.

(2) Porphyritic granular aggregates.

(3) Columnar crystals giving lath-shaped sections.

(4) Irregular grains.

(5) As skeleton crystals and microlites.

The porphyritic and other felspars of the rocks under consideration are usually twinned in two distinct types:

(1) The most common type is that known as the albite type. Here, the twinning axis is normal to brachypinacoid, which plane is also the composition plane. Rock making plagioclase is characterised by the frequent repetition of this twinning, so that a crystal consists of a great number of thin plates, which when reviewed under the microscope, give rise to characteristic bands of black and white as nicols are crossed.

(2) Twinning is also common according to "Pericline Law". The twinning axis is the macrodiagonal axis b. When polysynthetic, this gives another series

of fine striations seen on the bachypinacoid.

The porphyritic crystals often show zonal structure, which, according to Rosenbuch "is in very many cases simply a consequence of repeated interruptions in growth". In such cases it is frequently observed that the distance between succeeding zones is greater in the direction of the length than in that of the breadth of the crystal section; a fact which testifies to the unequal rate of growth in different directions. In other cases, however, a zonal structure is first noticeable between cross nicols by the fact that the extinction does not take place at the same time in the kernel and in the diffetent shells, but the kernel and shells extinguish light in azimuths. This phenomenon is explained by the assumption that the central crystal is basic and the succedding zones become more and more acid.

That consolidation under great pressure is not favourable to the formation of crystals, may be proved by some very interesting observations, made by Teall in connection with these porphyritic crystals. He noticed that the inner zones were not bounded by sharp angles, - being more or less rounded at the corners, whereas the external and, therefore, the last formed zones, often show a gradual approach to definite crystalline form. This seems to show that the conditions under which the development of the porphyritic crystals commenced were not favourable to the production of definite form, but they become more and more favourable as the growth progressed.

Distribution of the different varieties of plagiodase in the different classes of basic igneous rocks.

The original felspar of basic igneous rocks is of a basic character. Dr. Haughton found Anorthite from a sample of plagioclase-augite rock from Calingford County Down. The same mineral, but rather altered, was found by Dr. Hedde in the gabbros of Lendalfoot, in Ayrshire. Typical anorthite, however, appears to be rare, the most common variety being an intermediate composition between anorthite and labradonite.

In prophyritic rocks belonging to the dolerite family, it occurs as individual crystals and as grannular crystalline aggregates, which are sometimes completed externally by a felspar substance of a composition somewhat different from that forming the internal mass of the grains. Teall describes a variety from Tynemouth dyke illustrating this form of occurrence.

The dominant felspar of the ophitic dolerites of the Hartz have been shewn to be typical labradonite, composed of two molecules of anorthite and one of albite. (Ab_1 An_2).

From the foregoing remarks it may be concluded that the prevailing felspars in the basic division of the normal plagioclase rocks belong to the labradorite-anorthite group. At the same time there is evidence of the occurrence of felspar, more acid in character, especially at the junction line between rocks of normal basic and normal intermediate composition. As an illustration, Teall cites the Whin Sill, which has a silica percentage of about 50 and a sp. gr. of about 2.9, and so can be classed as a member of the basic family. From the result of analysis of the felspar extracted from the rock, it appears that the original felspar was andesine. This rock, although it shows traces of ophitic texture, does not attain this texture to the same perfection as is found in rocks in which the felspar is labradorite. Another point of importance regarding this rock is the presence of bisilicate enstatite in the place of unisilicate olivine.

The occurrence of oligoclase in basic rocks is rather rare. Nevertheless, in certain rocks of this division the felspar gives straight extinction in all longitudinal sections, and is, therefore, referred to this species.

Albite only occurs as a secondary product, and is frequently present in rocks that have undergone regional metamorphism.

The felspars of basic igneous rock are often altered by various metamorphic agencies. Though it is sometimes difficult to determine the exact nature of the alteration products, it is found convenient to describe them as sanssurite, - a term first applied by Saussure to "a tough compact, or fine grained, light coloured substance, possessing hardness of quartz and a specific gravity of from 3.32 to 3.4". Subsequent researches, however, have shewn that the composition of Saussurite is not constant, but varies considerably. The alteration of felspars by surface agencies gives rise, under certain circumstances, to the formation of zeolites. Under other circumstances, it produces a hydrated silicate of alumina from which the whole of lime and a part of soda and silica have been removed. These lime and silica are subsequently deposited in the veins of rocks as secondary calcite and quartz.

It has been mentioned above that Saussurite is not a definite mineral, but a substance of variable composition. From investigation of chemical and physical properties of Saussurite from certain Swiss gabbros, Dr. Hunt concluded that certain varieties might be regarded as compact zoisite. In 1883, elaborate chemical and microscopical researches enabled Cathrein to determine the nature of certain Saussurite. He found that the apparently cloudy and indistinct substance could be resolved into distinct minerals when viewed in thin sections and a magnifying power of 300 diameters. These minerals he proved to be zoisite, embedded in the colourless ground-mass of irregular grains, showing the twin structure of plagioclase. In certain cases, however, the embedded mineral proved to be Epidote, showing marked pleochroism, though, he says, no distinction can be drawn between zoisite-bearing and epidote-bearing saussurites. A bulk analysis by the same Author gives the following result:-

Orthoclase	-	8.0
Albite	-	41.0
Anorthite	-	1.7
Epidote	-	7.6
Zoisite	-	41.7
		100.0

Microscopic examination, however, revealed a few more accessory constituents, such as chlorite, actinolite, and calcite.

The principal conclusions of Caithrein's observations are summed up by Teall in the following:-

(1) The so-called saussurite is not an independent mineral, but a mixture of plagioclase (more rarely orthoclase) with zoisite, actinolite, chlorite, and other minerals occur as ~~necessary~~ accessory constituents.

(2) The chemical composition of saussurite mostly resembles that of the soda-lime felspars. It is, however, poorer in silica, richer in lime, and possesses a higher specific gravity.

(3) Saussurite is a product of the metamorphosis of the felspar through interchange of silica and alkalies

with lime, iron and water.

(4) The epidotisation of the felspar is an alteration process which stands in the closest relation to the formation of saussurite, (zoisitisation) and differs only in the fact that more iron is taken up.

The felspars of basic igneous rocks are rather susceptible to modification when subjected to mechanical stresses. The curvature of twin lamellae, and the fact that the extinction under cross nicols is not sharp and definite, all tend to show that the felspars are in a state of strain. It is also frequently seen that twin lamellae terminate abruptly at the cracks or run in from them in the crystal substance and then disappear. This fact tends to prove, at least to a certain extent, that the twin lamellation is a secondary structure.

Angite occurs in the basic igneous rocks as crystals, irregular crystalline masses, granules, and granular aggregates. The larger crystals are stunted in growth and are usually short as compared to their width. The smaller crystals, however, are generally elongated in the direction of vertical axis. The principal cleavages are parallel to the prismatic faces, which are inclined at an angle of 87°, so that a section across the crystal gives a rectangular figure with truncated corners and lines intersecting nearly at right angles. This test is very important for all petrographical purposes. Twinning is rather common, and when it occurs the orthopinacoid is both twin-plane and face of composition.

The double refraction is fairly high and in ordinary sections gives colour of the second order.

The colour of monoclinic pyroxenes varies considerably. Some are colourless in thin section, while others are brown, yellowish brown, or brownish-violet. It has recently been shewn that the brownish-violet colour of angite is sometimes due to the presence of certain amount of titanic acid. The augites of the basic igneous rocks are, as a rule, not pleochroic, though certain deeply coloured varieties do show slight pleochroism, as is found in the dolerites from Rowley Regis.

Augites, showing good external form, are comparitively rare in British basic rocks. They do, however, occur as porphyritic crystals in rocks of

Rowley Rag type. As a rule, the augite of gabbros and dolerites occurs in irregular masses, showing ophitic structure, and in basalts it occurs in granules and granular aggregates.

Diallage is a laminated variety of augite (Schillerised), usually of a greenish colour, and occurs in gabbro. The lamination is parallel to the orthopinacoid; it appears in thin section as fine lines, which are very characteristic of this mineral when viewed in thin section. The surfaces of this lamination or pseudo-cleavage, as they are sometimes called, show a pearly or sub-metallic lustre, due, perhaps, to the presence of minute included plates and rods.

As the result of surface weathering, the augites of basic igneous rock often change into a fibrous or granular substances of a greyish colour. They are also sometimes altered into scaly chlorite, which, under crossed nicols, shows a deep blue glistening light. This peculiar feature is common with the older pataeozoic dolerites, and sometimes, though not always, it forms a distinguishing feature from similar rocks of a newer age. (Tertiary). The non-aluminous augites, however, may give rise to serpentine.

The effect of contact metamorphism upon the augites of basic igneous rocks is very interesting. The augite may pass either to Uralitic hornblende or Actionolitic hornblende. The term Uralitic is applied when a crystal of augite is changed into hornblende without altering its external form. The term

Actinolitic, on the other hand, implies that the original form has more or less been destroyed. Speaking of the hornblende developed by contact metamorphism, Mr. Allport said "Like all hornblende it exhibits colours in polarized light and is dischroic: but the crystals differ in character from those occuring in diorites and other igneous rocks: nor are they the same as those forming the true hornblende-schist of the Lizard district, for example. They have often the character of actinolite, and are frequently aggregated in radiating groups, composed of flat blades of a bluish-green colour, and not very translucent. Occasionally, however, they are crystals quite similar to those in ordinary hornblende-schist".

The development of hornblende from augite by pressure or regional metamorphism may now be regarded as one of the most definitely established facts. This secondary hornblende may occur in the compact, uralitic, or actinolitic conditions. Diallage may be replaced by irregular grains of compact hornblende, the change commencing from the margin of the crystal and then proceeding inwards, until the change is complete. The "Uralite" does not, however, form a single compact crystal, but consists of numerous slender columns exactly parallel to one another. "Uralite" is always green, and exhibits the pleochroism of common green hornblende. Its sp. gr. is that of common hornblende.

It appears that, in the process of "uralitization", or transformation, a part of the lime separates out, for finely divided calcite or epidote often accompanies this "paramorphism".

In considering the distribution of augite and hornblende in basic igneous rock, Teall calls attention to the interesting point "that nothing strikes one so much as the evident instability of the former mineral at low temperatures, as shewn by its tendency to pass over into the latter". It is difficult to judge whether such a change is absolutely dependent on such conditions, although this change is more pronounced in areas which have been affected by regional metamorphism.

Rhombic Pyroxenes, are not very important constituents of British basic rocks, as their occurrence is rather rare. Their presence has been noted in the gabbros of the West of Scotland, and in certain finer grained rocks of the doleritic type. As for example, in certain portions of the Whin Sil in similar rocks from Ratho, near Edinburgh, and Kyloyth in the Campsic Fells. Prof. Judd has found hypersthene in a dolerite which forms a subordinate part in the great serpentine dyke in Forfarshire. While examining some of the Allport's rock-slides of Rowley Rag, I found some crystals in one of the slides, which are deep green in colour and give straight extinction, and so, doubtfully, may be relegated to hypersthene, although the characteristic pleochroism of hypersthene is not so pronounced. I shall, however, describe its occurrence in detail while dealing with the rocks of that area. In the rocks of gabbro family, the rhombic pyroxenes usually occur in grains without a definite external form. In the dolerites they show a more perfect form, but it is in andesites and porphyrites that we find them most perfectly developed. The prismatic angle of the rhombic pyroxenes agrees very closely with that of augite. In the massive varieties in the older rocks, besides the prismatic cleavage, there is always a more perfect one parallel to the pinacoidal faces (010). This last cleavage is seldom found in the crystals occuring in the prophyritic rocks and lavas. Cross sections of the massive forms, therefore, are traversed by a double system of cleavage cracks apparently intersecting at right angles, and bisecting each other's angles. "It is not unlikely", says Rosenbuch, "that the pinacoidal partings in some cases correspond to gliding planes, and are the result of mountain pressure, while in others they are brought about by the inclusion of foreign substances". In addition, an irregular cracking, approximately at right angles to vertical axis, is sometimes observed, and it is along these cracks that the decomposition of the mineral generally takes place.

The Rhombic pyroxenes may be divided into three sub-divisions, according to the percentage of iron (FeO) they contain:-

Enstatite	-	with less than 5% of FeO
Bronzite	-	5 to 14% of FeO
Hypersthene	-	above 14% of FeO

The Orthorhombic pyroxenes become transparent in various colours, according to the position of the section and to the iron percentage. Enstatite is almost colourless to greyish or yellowish-white; bronzite is yellowish to greenish; hypersthene green, light red, or brownish-red. The index of refraction is high, and appears to increase with the iron percentage; hence the marginal total reflection is strong, and the surface distinctly rough.

The double refraction is weak for members of the series poor in iron. Hence the interference colours are low for enstatite and bronzite, - not exceeding yellow of the 1st. order. For hypersthene they are noticeably higher, reaching red of the 1st. order in sections which are not too thin.

Olivine. This mineral plays a most important part in the basic eruptive rocks. It forms either well-developed crystals and incipient forms of growth, or irregularly defined rounded or angular grains, or finally, granular aggregates. Well formed crystals are, however, rare. When they do occur they give rise to sections, which are remarkable for their symmetry. These sections are six sided, and the terminal faces meet at an acute angle. Twins are of rare occurrence, the twinning plane being (011).

Its chemical composition is 2(Mg, Fe)O, SiO_2 In normal olivine the amount of ferrous oxide is generally less than 16%. The more ferruginous varieties are called hyalosiderite. This is the case with some of the olivine in the dolerites of Rowley Regis and the West of Scotland. Lastly, those with predominating iron percentage are called fayalite.

Olivine may be colourless, yellow, or yellowish brown. The depth of colour is a good indication of the amount of iron present. Varieties, which are not too poor in iron, become permanently red on being heated to redness, and then exhibit more or less distinct pleochroism; otherwise there is no appreciable pleochroism. The index of refraction is high; hence the relief is considerable and the surface decidedly rough. The double refraction is very strong, and the interference colours, even in quite thin sections, are of the 2nd. and 3rd. order.

The outline of the crystal sections often exhibits a decided rounding effect with variously shaped loops as the result of corrosion by the magma. From the same source is, perhaps, due the deep reddishs brown colour in the margin of some crystals in the dolerites near Portrush, while the interior of the crystal is quite colourless.

Olivine, in this section, is readily acted upon by hydrochloric acid, with the separation of gelatinous silica. By this method it can be distinguished from some pyroxenes with which it may be confused.

According to Rosenbusch, olivine may be distinguished in three different kinds, in accordance with its mode of occurrence: (1) "olivine of the granular eruptive rocks, (2) olivine of the porphyritic eruptive rocks, and (3) olivine of the crystalline schists".

The olivine of the granular eruptive rocks, as it occurs in olivine diabases, olivine gabbros, olivine norites, and peridotites, and as it is found in the older segregations of the volcanic rocks, exhibits no perfectly regular crystallographic boundary. It is always evident that it is older than the other silicates accompanying it, and from the nature of the decomposition processes, it is clear that very ferruginous varieties do not occur. These olivines enclose crystals of magnetite, ilmenite, apatite, and chromite. In many gabbro and norite occurrences they are crowded with needles and tabular microscopic interpositions, which are arranged parallel to the three principal sections and possess a metallic habit; they appear to be ti anaferous iron compound. Fluid inclusions are not infrequent.

The olivine of the porphyritic eruptive rocks (melaphyres, basalts, basanites, nepheline, and leucite-basalts, limburgites), belong to the secretions of the first period of consolidation; their crystallization immediately followed that of the apatites and iron ores, and preceded that of mica and bi-silicates. Hence, it appears in crystal forms, which, however, are very often disturbed by subsequent corrosion. Pockets and inclusions of the ground mass are very characteristic of this variety of olivine, as are also the glass inclusions of manifold shapes, irregular inclusions of fluids, among which is liquid carbon-di-oxide, and interpositions of the older minerals associated with it, especially magnetite, ilmenite, chromite, and picotite. Ferruginous varieties are very common in these rocks. Here also are found skeleton crystals and incipent forms of growth which are found in glassy rocks, which only reached incomplete crystalline development; they often enclose remarkably large portions of the rock glass arranged symmetrically. Indications of a second generation of olivine crystals in the porphyritic eruptive rocks are rarely found. Olivine appears as an accessory constituent even in rocks of the tachytic and andesitic series, quite ribh in alkalies and poor in bivalent bases, and often stands peculiarly correlated to orthorhombic pyroxenes.

In the Archaean rocks, olivine is sometimes an accessory constituent, sometimes an essential constituent in a series of rocks which occur in the form of inclusion. The olivine of these rocks has the same habit as that of the granular eruptive rocks.

The alteration of olivine is very interesting on account of the manifold products that it gives rise to. Rosenbuch enumerates three different processes:-

(1). Due to general weathering, water, oxygen, and carbonic acid, leading to the formation of carbonates, silica, and limonite, with a variable amount of serpentine. This serpentinization may possibly be the first stage in this process of alteration. The invariable presence of a certain amount of calcite rather suggests as though this process of alteration was accompanied by impregnation.

(2) The second process, which is by far the most common one, is the alteration of olivine to serpentine. The change starts at the surface, along cracks by the formation of yellowish-green fibres, accompanied by the separation of magnetite and other iron-oxide. The

fibres stand perpendicular to the cracks, thus giving rise to a net-like appearance. As the process advances, new cracks are formed along which serpentization continues until all traces of the original mineral are obliterated.

Although the serpentization of olivine in many cases may be a simple act of weathering, yet in others it is probable due to the action of warm waters. The ferric oxides produced from the decomposition of highly ferruginous olivine (hyalosiderites and fayalites) may secondarily pass into hydrous oxide of iron. This latter change may sometimes impart a pleochroism to the olivine which did not previously exist.

(3) The third process is the alteration of olivine to amphibole; it is confined to both schistosk and

eruptive rocks of pre-cambrian age. It has, however, been shewn that this alteration is dependent upon the mutual influence of olivine and the adjacent rock constituents. The products of alteration are first confined to the periphery of the olivine, and advance from here inward. The needles of the amphibole minerals which may be referred to a conglomeration of tremolite, actinolite, and anthophylite, stand at right angles to the boundary of olivine, and arrange themselves in several zones, differing in colour. To the same group of observations may be added the phenomenon of alteration of olivine to a "felt of amphibole needles", with an admixture of chlorite or serpentine and magnetite, which is often called 'pilite'.

Hornblende. This mineral occurs as an original and also as a secondary product in basic eruptive rocks. Original hornblende is comparatively rare. Basaltic hornblende is almost always well crystallized; when in more or less rounded grains, it is evident that the crystalline character has been either lost through mechanical processes or by the action of magma on previously formed crystals. The forms in the zone of vertical axis are those of prisms (110), the clinopinacoid (010), and sometimes orthopinacoid (100). The crystals are usually elongated along the vertical axis and terminated either by clinodomes or by basal planes (pinacoids 001). The prismatic angle is about 124°. Cleavages, parallel to prisms, are very pronounced so that, in cross section, the two sets of cleavages appear to cross each other at 124° and 56°. This forms an important diagonastic character for the determination of the mineral under the microscope, when definite form is wanting. Longitudinal sections show parallel cracks and give extinction angles varying from 0°, when the section is parallel to the orthopinacoid (100), to 20° or less, when the section is parallel to the clinopinacoid (010). The optic axial plane is also the plane of symmetry. The crystals are twinned in such a way that the orthopinacoid is both twin plane and face of composition.

It occurs in a dolerite from Necropolis Hill, Glasgow. In some Warwickshire basic diorites, Allport found hornblende, showing ophitic structure, although well formed crystals are not uncommon. In the Whin Sill and in a "greenstone" from St. Minver in Cornwall, brown hornblende and augite are intergrown.

A peculiar variety is the so-called reedy hornblende, which consists of "approximately parallel columnar to fibrous amphibole aggregates with a light green colour and slight pleochroism, and which is usually mixed with epidote and chlorite, and is common in certain eruptive rocks of the diabase family and in many amphibolites". In many cases, however, it may be proved that the hornblende is of secondary origin and that it has been derived from augite (uralitic). Common hornblende is mostly green. The pleochroism is confined to green tones. The rays vibrating parallel to (a) appear yellow, those parallel to (b) yellowish, and the rays parallel to (c) have a tinge of blue.

As a result of weathering, hornblende may change into chlorite, with the secretion of epodote or calcite and quartz. Since chlorite may further alter into a mixture of carbomates, clay, limonite, and quartz, it is evident that psendomorphs of these minerals may be formed after amphibole. The hornblende becomes fibrous during chloritization.

Magnetite and Ilmenite. Oxides of iron, with a variable amount of titanic acid, are almost always found in basic eruptive rocks. They occur as crystals, skeletons, and grains. When in crystals, the predominant form is octahedron, twinning according to the spinel law, the twinning plane being the octahedral face. Simple crystals sometimes grow in a parallel position. In rocks which contain a glassy base, minute crystals and grains of magnetite are often seen to be arranged in straight lines so as to form rods.

Ilmenite occurs in irregular masses, but sometimes it occurs in beautiful hexagonal tablets, as is found in the dolerites of Rowley Regis.

Black Mica. A hydrated silicate of alumina, iron, magnesia, and potash. Under the microscope the mineral appears in plates, scales, and lath-shaped sections, the latter showing intense pleochroism. (pale yellow to chestnut brown and black). The principal absorption takes place when the long axis of the lamella, or the trace of the cleavage, is parallel to the short diagonal of the polarizing nicol.

STRUCTURES.

Structures in igneous rocks may be classified primarily into two groups:-

(a) Macroscopic, or structures which are recognised in the field. They are often developed on a large scaleand are easily detected with the naked eye. They may be called the external structure.

(b) Microscopic, or structures so finely developed as are only recognisable under the microscope. It is sometimes called the micro-structure or simply the texture of rocks.

(a) The macroscopic or the external structure of rocks. Igneous rocks are, as a general rule, said to have a massive character in contradistinction to the bedded character of sedimentary rocks. There are, however, exceptions, as in the bedded lavas, where the different bands represent distinct outflows. Again, the differential movement of the different parts of a lava flow in a plastic condition may produce what is known as 'fluidal' or flow structure on consolidation.

Shrinkage or consolidation from fluid to solid may develop 'joints', which are so common in all igneous rocks. Sometimes these joints are developed in more than one plane, giving rise to triangular, quadrangular, pentagonal, and hexagonal prisms. An admirable illustration is afforded by the basic rocks forming the noted Giant's Causway.

When an igneous rock contains a number of more or less spherical or elliptical cavities, due to the escape of gases and vapours during the process of cooling, it is said to be vesicular. When the vesicles are numerous, as in pumice, it is said to be pumiceous or scoriaceous. The cavities are sometimes filled with secondary minerals, which are then called amygdules and the structure amygdaloidal. Amygdaloidal structure is typically found in volcanic and hypabyssal rocks, and not in plutonic rocks, although in some granites, which have consolidated under comparatively low pressure, are found small irregular cavities, from which project well shaped crystals. This structure is known as miarolitic or 'drusy' structure.

Some granites show dark coloured patches, - the heathen of quarrymen. These are probably, in many cases, due to the segregation of basic constituents in the earlier period of solidification. But in some cases, especially when occurring in the marginal part of the intrusive mass, they are, undoubtedly, included fragments of foreign materials, caught up by the magma during the intrusion. Sometimes these dark patches occur in such abundance that, by their parallel arrangement, they impart a banded or gneisose structure to the rock.

In some rocks, the surfaces of separation appear to form large concentric shells. This character is particularly characteristic of the rock known as phonolite, which has a tendency to split into slightly curved plates.

(b) Microscopic Structure or Texture of Rocks: A thin ~~surface~~ Section of a rock, when examined under the microscope, appears to be composed either entirely of crystals, crystals mixed with glassy material, or entirely of glass, and accordingly the rock is said to be either crystalline, hypo-crystalline, or glassy.

The internal structure of a rock depends on the relation of the crystals to one another, or the crystals to the ground-mass, if any present.

Rock magmas, when solidifying under conditions which allow of a slow cooling process, have time enough for the molecules to arrange themselves into definite mineral bodies, thus producing crystalline or hypo-crystalline textures. When such conditions are absent, as when the magma cools rapidly, the production of glass results. Thus, it is quite natural, that, in nature, we should meet rock masses similar in composition, but widely varying in texture, depending on the process and environment attending the consolidation. Again, for the same reason, it is equally reasonable to expect a continuous gradation between the two extreme textures, - crystalline and vitreous.

Vitreous or glassy material, though apparently devoid of crystals, are not entirely so, as is proved when a thin section of such a material is examined under the microscope with a high power. Scattered in the ground-mass of such a section are seen numerous minute spherical, rod-shaped and hair-like bodies, which can be described as the first stage towards crystallization. They are not actual crystals, as they do not react on polarised light. They are generally called crystallites, although some varieties have got specific names. Thus round bodies are called globulites rod-shaped ones, belonites, and coiled ones, trichites.

Besdies the crystallites there are rod-shaped bodies called microlites. They differ from crystallites in that they react on polarised light, and can be referred to some definite minerals. They can be described as an intermediate stage between crystallites and the formation of actual crystals. Another very interesting texture, the spherulitic, is found in both volcanic and hypabyssal rocks, although it is in the rhyolites and pitchstones that spherulites of great prefections are met with. The essential feature of spherulitic structure, according to Iddings, is crystallization about a centre or about a number of neighbouring centres, with a radiating or divergent arrangement.

All spherulites can be divided into two groups:-

(1) When the fibres are composed of a graphic intergrowth of felspar and quartz.

(2) When the fibres are chiefly composed of felspars.

Group (1) is characteristic of some acid hypabyssal rocks, to which Rosenbuch has given the name of granophyre. Similar spherulites are also met with in rhyolitic lavas and pitchstones. Harker is of opinion that a magma having eutectic composition, when consolidated not too rapidly, has a tendency to produce radiating graphic texture of this kind. Under the microscope such a texture is characterised by "black cross effect" when the nicols are crossed. The spherulites of group (2) are chiefly found in acid volcanic rocks. The larger spherulites of this nature, often measured by inches, are always of a complex nature, the radiation starting from different centres. (Harker, Igneous Rocks. pp. 273-274) The delicate felspar fibres are often bifurcated at their ends, giving rise to a tufted or plumose appearance.

The fibrous habit of spherulites is suggestive of rapid crystallization from a highly supersaturated solution, and, perhaps, this was their mode of origin. The crystallization at isolated centres is due to the local richness in dissolved water vapour, reducing the viscosity in those places. The porous nature of the spherulites is connected with the liberation of steam in the process of crystallization.

Spherulites in basic rocks are of less frequent occurrence than in the acid rocks. Some very interesting examples have been noticed by Harker in the tachylitic margin of dykes and sills among the Tertiary Igneous Rocks of Skye. They are generally very small, and their true nature is much obscured by secondary changes. In these spherulites, when examined under the microscope, the characteristic dark cross appears much distorted and irregular.

The fact that microlites are often seen occurring within spherulites clearly proves that they are the production of the final period of solidification or even later.

A very important structure, common to volcanic and hypabyssal rocks, is the porphyritic. By this is meant the occurrence of some constituent or constituents of a rock in two distinct generations, referable to different stages of consolidation of the magma. The crystals of the earlier generation are called phenocrysts, and usually are of a larger dimension. In the volcanic rocks, the phenocrysts are in the main of intratelluric origin, - that is, they were formed prior to the extrusion of lava; while the ground-mass, including the later generation of the same minerals, crystallized after extrusion. Thus, the two periods of generation were separated by a break in the physical condition, namely, the sudden dimunition of pressure, accompanied by rapid cooling and probably loss of some volatile constituent of the magma.

In Hypabyssal rocks, the phenocrysts have been formed, or at least began to be formed, when the magma was contained in the lower level of the earth's crust. But, in general, their formation and growth seems to have occurred 'in place' under the same conditions as the groundmass. This is proved by the fact that large porphyritic crystals are often found in the central part of a laccolite, whereas they are absent in the marginal parts. Besides, the phenocrysts in an intrusive rock do not always conform to the direction of flow, but tend to have a radial structure characteristic of formation 'in place'. In many cases they are found to contain apatite and other minerals of earliest crystallization.

When a magma is consolidated at a great

depth within the earth's crust, it is evident that the rate of cooling is extremely slow. As crystallization takes place, heat is liberated. It may so happen that the liberated heat is greater than the heat lost by conduction. As a result, the temperature rises until the melting point is reached, when equilibrium is established between crystals and magma, and, thenceforth, the existing crystals will continue to grow but no new ones will be initiated. The less the degree of supersaturation reached, and the sooner the equilibrium established, the fewer will be the centres of crystallization started, and the larger the completed crystals. It is quite probable that, under abyssal conditions, plutonic magmas in general crystallize without attaining great degree of supersaturation, and their coarse texture is in accordance with such supposition.

Plutonic rocks are as a rule non-porphyritic, although Michel Levy recognises, even in normal granitoid rocks, two distinct periods of consolidation. It is quite possible that, the whole process of crystallization being effected within a moderate range of supersaturation, the crystals of the first phase continued to grow until the magma was exhausted without fresh centres of crystallization being set up. Such a rock may be regarded as consisting wholly of overgrown phenocrysts.

It has been mentioned before that the micro-structure of rocks is determined both by the shapes of the constituent crystals, and by the arrangement with respect to one another and to the glassy base.

(a) As regards the shape of the crystals:-

(1) When their faces are well developed they are called idiomorphic.

(2) When their faces are not fully developed they are called allotriomorphic.

(b) As regards the arrangement of crystals with respect to one another, we may have:-

(1) Juxtaposition, - in which case, although subordinate minerals may be enclosed in the preponderant ones, the preponderant minerals are adjacent to one another. This may occur as:-

(a) An allotriomorphic granular texture when the crystals are without properly developed faces, but are of a uniform size. It is sometimes also called a granitic structure.

(b) Hypidiomorphic granular texture. Similar to (a) but crystals showing their faces partially developed.

(c) Pan-idiomorphic granular texture, in which the crystal faces are well developed.

(11) Interposition.

(a) Graphic structure (including micro-graphic and cryptographic). In this the two minerals mutually enclose one another by interpenetration. Pegmatites are familiar example of this kind of growth. A primary graphic intergrowth clearly proves the simultaneous crystallization of two minerals involved, and maybbe interpreted as an eutectic mixture.

(b) Poikilitic or Poecilitic structure is that in which optically continuous crystals of one mineral play the part of matrix for crystals or grains of another, which do not show parallel orientation.

A variety of poikilitic structure is the ophitic, - a structure so characteristic of dolerites. Prof. Judd suggests that, for the production of this structure, the molten mass must be in a state of internal equilibrium. That is to say, where there is no kind of movement, whereby strains and tensions can be produced in the viscous matter during consolidation. Conditions like these are best attained in intrusive masses, Where the rate of cooling is somewhat more rapid than in plutonic mass and pressure moderately high. Once the magma is injected between strata, it remains there in a state of perfect immobility.

Porphyritic Structure: This has already been discussed. Prof. Judd gives the name 'glomero-porphyritic' to a structure in which fragments of troctolite are found embedded in an ophitic dolerite. Another explanation is, that anorthite and olivine had separated around certain centres, and new conditions induced the crystallization of the rest of the magma as an ophitic dolerite.

Orbicular Structure: in which the definite minerals are grouped radially or concentrically round a common centre to form spheroids.

Structures due to movements:

In a rock wholly or largely crystalline, differential movement during the period of consolidation may impart a very distinctive granulitic habit to some of the constituent minerals.

It has been mentioned that for the development of ophitic structure the magma should be in a state of perfect internal equilibrium. Judd, in describing the Tertiary dolerites of Scotland and Ireland, points out that when the rock crystallized free from disturbance the augite enclosed the felspar crystals; but with contemporaneous movement intricate shapes could not form, or were immediately broken up, and the augite appears as aggregates of granules in the interspaces between felspars.

TERTIARY IGNEOUS ROCKS.

The region within which volcanic activity manifested itself, during Tertiary time in Great Britain, ca not be strictly defined, but if restricted to those parts of the country where igneous rocks, probably of that age, now appear at the surface, we find that it includes the North of England and of Ireland, the Southern half and West Coast of Scotland, - a total area of more than 40,000 square miles. Over that extensive area volcanic phenomena were displayed during an "enormously protracted geological time". So prolonged was the duration of the eruptions, that there was enough time for enormous topographical changes from denudation, and also for "considerable variation in the fauna and flora alike of land and sea".

Owing, perhaps, to secular terrestrial contraction, the volcanic region underwent elevation, with a sea of molten magma gathered underneath it. Consequent to enormous horizontal tension, the crust was ripped open by approximately parallel fissures. No sooner were the fissures formed than they were injected with the molten magma from underneath, thus giving rise to the numerous basic dykes.

Where the fissures reached the surface, the lava formed enormous plateau, filling up the great valleys, great parts of which have since been denuded.

Volcanic Plateaux.

The superficial records of Tertiary volcanic action have been, by the action of enormous denudation, reduced to broken and isolated fragments. The chief volcanic tract lay to the west in a broad and long depression, that stretched from the south of Antrim to the Minch, - covering an area of 250 miles x 25-50 miles. Nor the outburst was limited to this comparatively small area. Similar rocks are found in the Faroe Islands. Closely connected are, perhaps, the volcanic rocks of Iceland and Greenland. (Trans. Roy. Soc. Edin. Vol. 35. p.75).

Petrography. - There is a comparatively small variation, the rocks consisting mostly of dark basic lavas. Intercalated between the lava sheets, occur layers of volcanic and even non-volcanic fragmental rocks. The lavas range from coarsely crystalline to a "dense variety in which a few porphyritic crystals may be detected". Glassy variety is nearly absent. Most of the rocks are dolerites, and some are basalts. They are chiefly composed of lath-shaped clear crystals of felspar enclosed in large plates of augite. Olivine is not common, but large quantities of magnetite occur.

In a few localities there is found, intercalated with ordinary basalts and dolerites, a pale amygdaloidal rock with lower specific gravity. When examined under the microscope it appears to be composed chiefly of felspar. Dr. Hatch suggests that the rock originally consolidated as a glass, poor in iron and magnesia, the development of felspar being due to devitrification. The lavas can be distinguished in three distinct types:-

(1) Massive and amorphous. - The dolerites occur mostly in thick masses, without any structure, except

the usual irregular joints, placed perpendicular to upper and under surfaces.

(2) Prismatic structure is typical of the more compact heavy basalts. The rocks are traversed by vertical joints producing (a) polygonal columns, and (b) "starch like" aggregations, as at Giant's Causeway and at Staffa.

(3) Amygdaloidal structure is developed throughout the whole series of basalts. Even where the basalts present perfect prismatic structure, a foot or so of the rock at the bottom shows vesicular structure. The amygdales are filled with secondary minerals.

Areas of the Plateaux and succession of rocks in them.

Four distinct districts are recognised at present:- (1) Antrim, (2) Mull, (3) Small Isles, and

(4) Skye. To these must be added Shiant Isles and St. Kilda. Whether or not each of them was an isolated area of volcanic activity, cannot now be determined. It is quite probable that their present isolation is due entirely to subterranean movements and denudation.

(1) Antrim. - The largest of the basalt-plateaux of Britain. It has an area of nearly 2,000 square miles stretching from Lough Foyle to Belfast Lough and from Rathlin Island to "beyond the southern margin of Lough Neagh". The basalts lie on white chalk, and in places over Lower Carboniferous. The existing thickness of basalt in Antrim is about 1,000′. An horizon of tuff occurring in the basalts divide it into an upper and a lower division. The lower division, which is about 400′ - 600′ in thickness, is distinguished by

celluloid and amygdaloidal structures. The upper division, which is also about 600' thick, rests on a ferrugenous bed or sometimes directly on the lower division. The lower part of this division forms the celebrated Giant's Causeway. The general character of basalt is more frequently columnar, black, and compact, and with fewer examples of the strongly amygdaloidal structure so conspicuous in the lower group.

(2) Mull. - This plateau, besides the Island of Mull, embraces a portion of Morven, and, stretching across Loch Sunart, includes the western part of the peninsular of Ardnamarchan. That it formerly extended beyond its present limit, is indicated by its margin of cliffs and fringe of scattered island and outliers. It extended as far as the Treshinish Isles, which are

composed of basalts. On its eastern border, a capping of basalt on the top of Ben Iadian in Movern, and others further north, prove that its volcanic sheets once spread far into the interior of Argyleshire. On the south its fine range of lofty hills, with their horizontal layers of basalt, bear witness to the diminution which it has undergone on that side, while on the north, similar sea-walls tell the same tale.

Geikie estimates the thickness of basalts in Mull as 3,000 feet. They are found to rest on Cretaceous and Jurassic rocks. The lowest beds are basalt-tuffs, intermingled with sandy and gravelly sediment as if volcanic debris had fallen into water where such sediment was in course of deposition.

The basalts of Mull have been greatly metamorphosed by later intrusions,- composed chiefly of dolerite, gabbro and granophyre, with various allied kinds of rocks.

(3) Small Isles. - This plateau, the smallest and the most discontinuous of the four, includes the Island of Eigg, Rum Canna, and Muck. That the fragments of the bedded volcanic masses preserved on each of these islands were once connected, can hardly be doubted. The thickest mass of volcanic sheets occurs in Eigg, where, lying unconformably over Jurassic beds, they attain a thickness of 1,100'. They consist of black, fine grained columnar and amorphous basalts, more coarsely crystalline dolerites, and dull earthy amygdaloids with red partings, and occasional thin bands of basalt, - conglomerate or tuff. Like the rocks at Mull, they have suffered from later intrusions.

(4) Skye. - This is the largest and most important of Scot ish areas. Comprising the Island of Skye, at least as far south as Loch Eishort, the west side of Scalpa and the southern half of Raasay, and probably extending to the Shiant Isles, it may be reckoned to embrace an area of not less than 800 square miles. The rocks form prominences with truncated top, rising sometimes a thousand feet high.

The hills everywhere present curiously tabular form that bears witness to horizontal sheets of rock of which they are composed. In the district of Totternish, the basalt hills reach a height of 2,360 feet, and along the western side of Skye the basalts sink below the level of the Atlantic.

THE BOSSES OF GABBRO.

When the basic lavas had built plateaux of several thousand feet in thickness, another volcanic activity took place. This consisted in the uprise of coarsely crystalline basic rock, which ultimately solidified as gabbros, dolerites, troctolites, and picrites. Rising as huge bosses through the already formed fissures, they lifted the overlying bedded basalts, and at times forced their way in between the strata.

Long after the formation of the gabbros, the subterranean action once more renewed and gave rise to another outburst. This time the materials were distinctly acid in character, (granophyre) and poured out from small cones which were probably very similar to the puys of Auvergene of the present day.

Following the uprise of Granophyre, the crust was once more ripped open and injection of basic dykes took place.

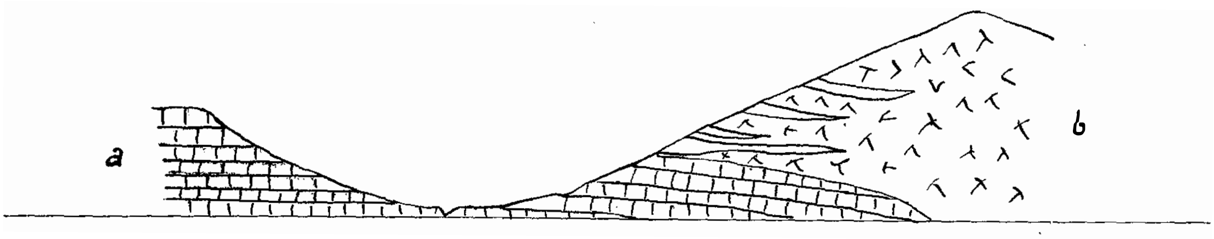
These Bosses are of two characters, (1) Basic, and (2) Acid. I shall here confine myself to the description of (1).

<u>Petrography of Basic Bosses</u>. There is a considerable variation both in petrographical structure and chemical composition in the rocks forming these bosses. At one end of the series we find rocks, composed chiefly of augite and plagioclase, which, though wanting in olivine, have the general structure and habit of dolerites. At the other end are mixtures, wherein felspar is either rare or entirely absent, and olivine

is the chief constituent. Between these two extremes are many intermediate grades, of which the most important are those containing diallage (a variety of augite) and olivine. These are the olivine-gabbros which form so marked a feature in the central parts of the great basic bosses. That some of the rocks pass into each other cannot be doubted. Their distinctive composition and structure seem to be dependent on their relative position in the eruptive mass. The outer and thinner sheets are dolerites with little or no olivine. The coarse gabbros occur in the inner portions. Rocks rich in olivine, however, are found at the outer and especially in the lower part.

<u>Distribution of Gabbros.</u>

(a) Skye. - By far the largest and most



Section across Glen-Brittle showing the general connection

of the bedded basalts (a) and the gabbros (b).

M. S.

important in Great Britain. Its chief portion is that which rises in the Cuillin Hills. The connection of its geological structure and age is best seen in the section.

(b) Both in Cuillin Hills and Rum "there is a structureless central region where the rocks are more coarsely crystalline, and an outer marginal belt, where they assume a bedded character and become finer in grain."

The rocks of Rum were described by McCulloch as composed of varieties of "Augite-rock". Prof. Judd observes "that the great masses of gabbro in Rum show psendo-stratification, so often observed in igneous rocks".

(c) Mull. - The rock, which is a coarse-grained gabbro, is distributed in innumerable sheets interposed between the plateau basalts.

INTRUSIVE SHEETS AND SILLS OF THE PLATEAU.

Closely connected with the volcanic rocks are the intrusive sheets that run in the underlying sedimentary beds of the country. The metamorphism of Portrush liassic beds is due to such intrusion, and has already been referred to.

The most important example of such intrusions occur in Fair Head. Here the sheet, composed chiefly of coarsely crystalline olivine dolerite, and having a thickness of about 200', lies on black carboniferous shales. But, that it is classified with Tertiary volcanic series, is demonstrated by its relation to the Chalk at the eastern end. It has, there, broken through that rock and changed it to marble, but at the western side the rock splits itself into a dozen sheets, and, in passing through carboniferous shales, gradually dies away. Similar intrusions are found all along the Inner Hebrides in the lower part of the basalt.

TWO TYPES OF INTRUSION.

The dykes are not uniformly distributed. Sir A. Giekie consideres them as the products of two different periods of eruptions.

Nature of Component Rocks. Basic. - Generally broad and long ones are coarser than short and narrow ones. To every dyke there is a salvage of finer material along the border. This is due to sudden chilling effect, and is helpful in determining the relative age of two intersected dykes. The finer material is sometimes abruptly terminated by glass. Curiously enough, the latter is sometimes found entangled within coarser variety. This is perhaps due to subsequent injections in the fissures of already formed dykes.

Porphyritic crystals occur, having their longer axis pointed in one direction, thus showing flow structure in big scale. The presence of amygdules is interesting. They are smaller and more uniform than those met with in volcanic rocks. As the result of cooling, the dykes are traversed by transverse cracks or more rarely, both by horizontal and transverse joints. As Geikie remarks "they are of considerable importance and interest, in as much as they furnish a ready means of tracing a dyke, when it runs through rock of the same nature as itself, and also help to throw some light on the stages in the consolidation of the material of the dyke".

Microscopic Character. The rocks are essentially a mixture of a plagioclase felspar, pyroxene, and iron oxide, and sometimes olivine, usually with some interstial matter. The felspars may be either labradorite or anorthite. The pyroxene in most cases is augite, but is sometimes enstatite and less frequently hypersthene. It may occur in regular or broken crystals, granular masses, or as single granules.

The iron oxide is either magnetite, ilmenite, or some other titaniferous variety. Some apatite. In the glassy material the different stages of devetrification may be studied. The most interesting example occurs in the Eskdale dykes. The central core is pure glass, but, by streaks and curving lines of darker tint, shows beautiful flow structure. This gradually ends with the appearance of globulites.

Structure.

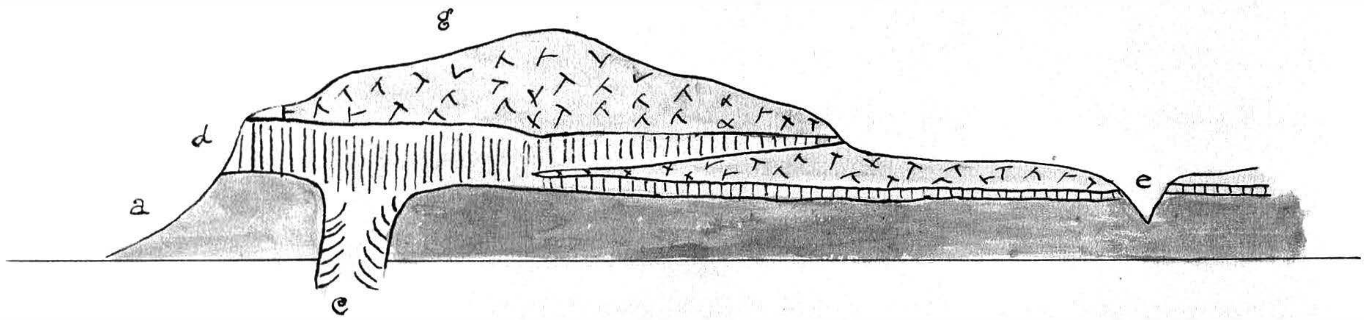
(1) Holocrystalline with a little glassy material. This type includes dolerites and basalts, characterised by ophitic structure and also in being rich in olivine. The rocks are in general more basic than the following type.

(2) In this there is a marked proportion of interstetial material, and absence of ophitic structure and olivine. Recently named by Rosenbusch as Tholerites.

Hade. Nearly vertical; sometimes with a mean inclination of about 13°.

The dominant trend of the dykes is from N.W. to S.E. and is very persistent in character.

Connections between dykes and sills. It is quite natural to think that interbedded igneous materials



a --- shales

c --- dykes

d -- intrusive sheet

e --- fine-grained basalts

g --- granophyres

m.s

quartzite. Curiously enough, metamorphism has been wrought more by sills than by dykes. The famous rock of Portrush is a good example, which shows how liassic shales can be "porcellanised".

Relation of Dykes to Geological Structure. The dykes are remarkable for their extraordinary independence of geological structure. They cut parallel bands of pataeozoic and mesozoic rocks without being affected as regards their trends. They cross faults with equal persistence.

THE BASIC IGNEOUS ROCKS OF CARBONIFEROUS AGE.

The volcanic history of carboniferous period is almost restricted to the earlier half, namely, the period represented by carboniferous limestone and millstone grit. In Ireland, in the Midlands of England, and further North in Scotland, the igneous rocks are associated with limestone series.

The following table, drawn after Geikie, gives the distribution of igneous rocks as regards time during the carboniferous period in Great Britain.

	England.	Scotland.	Ireland.
Coal Measures.			
Millstone Grit.		│	
Yoredale Beds.		│	
Mountain Limestone.		│	│
Lower Limestone Shales.	│	│	│

The igneous action was most intense in Scotland, and the great variety of rocks developed there makes the study very interesting. They were distributed over the wide Central Valley, from the south of Cantyre to beyond the mouth of the estuary of the Forth. Their remains spread as far south as the boundary of England, where they gradually vanish. But further down, they reappear again in Derbyshire.

The volcanic accumulations are the results of two types of eruption, namely, (1) Plateaux, (2) Puys.

(1) In the plateau type, the materials were discharged from vents or fissures, and which formed enormous table-lands, sometimes 1,000′ thick.

(2) In this type fragments of rock with some basic lavas were discharged from isolated

small vents, similar to those now existing in Auvergne. The puys did not start until some of the volcanic plateaux had become extinct.

A. Scotland.

(a) Plateau in Scotland. This phase of volcanic action was especially characteristic of the carboniferous period in the south of ~~England~~ Scotland, but does not appear elsewhere in the same system in Britain. On the whole, it preceded the Puy type of eruption, although, in the Midland Valley of Scotland, the two types appear to have been contemporaneous, at least for a short period of time.

Distribution. Rocks derived from this type of eruption are found to form plateau of (1) Clyde, (2) The

East Lothian or Garleton, (3) Mid-Lothian, (4) Berwickshire, and (5) The Solway. The materials forming these plateaux are chiefly andesite and altered poprhyrites. At the bottomof flows, however, and consequently the first products of the outflow, are rocks which are distinctly basic. Of these basic lavas the most conspicuous examples may be seen at Arthurseat, Calton Hill, and Craiglockhart.

Some of the rocks of Garleton plateau have been analysed by J. S. Grant-Wilson, with the following result:-

	Kippie Law sp. gr. 2.8	Hailes Castle sp. gr. 2.76	Markle Quarry sp. gr. 217
SiO_2	46.01	49.07	49.54
Al_2O_3	19.19	19.43	22.23
Fe_2O_3	5.91	10.58	9.55
FeO	6.75	2.35	1.12
MnO	0.19	0.32	0.08
CaO	8.68	7.87	7.19
MgO	6.81	4.36	2.80
K_2O	1.20	0.98	1.81
Na_2O	3,27	3,31	4.56
H_2O	3.07	2.26	2.42
Total	101.08	100.53	101.30

At the close of carboniferous limestone period, the eruptions of plateau-type had ceased, and were followed by the Puy type. These were small volcanic cones, which threw out, in most cases, merely tuffs, though in a few cases they poured forth lavas and piled up volcanic ridges. The evidence of these less vigorous actions are found by:-

(1) Contemporaneous sheets of basaltic lavas and layers of tuff intercalated in the sedimentary deposits,

(2) By necks of tuff, agglomerate or different lava-form rock, and

(3) By sills, bosses, and dykes.

The chief characteristics which distinguish them from those of plateaux are "the comparatively small thickness of the accumulations usually formed by these vents, their extreme local character, the numerous distinct horizons on which they appear, and the ultimate way in which they mingle and alternate with the ordinary carboniferous strata". (Ancient Volcanoes. Geikie. p.414).

(b) Distribution of Puy Type.

The basin of Firth of Forth may be taken as a typical area. There are abundant traces, besides, to the West of Pentland Hill.

The rocks of this type have been classified on petrotogical grounds after a careful microscopic examination by Prof. Watts. The great majority of the rocks are dolerites and basalts. They may be divided primarily in two divisions, - (1) rocks with olivine, and (2) rocks without olivine. Each division again may be subdivided into (a) dolerite group, with ophitic and sub-ophitic structure, and (b) basalt group, in which the groundmass is made up of felspar and granular augite; the idomorphic augite being embedded in fêlspar substance.

The term "sub-ophitic" is used by Watts in the sense that the augite grains are neither very large nor very continuous, optically, and that they rarely contain entire felspar crystals embedded in them, merely the end of the crystal as a rule penetrating in them.

Olivine-dolerite. Generally pophyritic. Phenocrysts of olivine, or of both olivine and felspar. In all cases the groundmass is sub-ophitic.

Olivine basalts. Porphyritic crystals of olivine, augite, and felspar, or of olivine and augite, and in some cases only of olivine. The groundmass is made of idiomorphic or granular augite and lath-shaped felspars.

Olivine-free dolerites. Felspar, augite, magnetite in coarse grained aggregate; usually with ophitic or sub-ophitic structure, groundmass not plentiful.

Basalts. Finer grained rocks, generally with a porphyritic ingredient and much scattered interstial matter in the groundmass.

The great majority of the Puy-lavas belong to olivine bearing series. A few of them are dolerites, but most are true basalts. The rocks show a variety of structure in the field. Some are solid, compact, black rocks not infrequently columnar, and weathering into spheroidal forms. Others have somewhat granular structure, weathering into brown amygdaloids. Many of them exhibit slaggy structure at their upper ~~end~~ and under surfaces.

The greater number of basic sills, bosses, and dykes associated with the puys are dolerites without olivine.

The non-olivine bearing basalts are found in various bosses and sheets in the basin of Firth of Forth.

The vents of Puys are not so numerous as those of Plateaux. They are sometimes arranged in lines suggestive of fissure underneath. But in other cases they are grouped irregularly. A remarkable instance of the former case is made by the chain of necks which extends from the vale of the Tweed at Melrose south-westwards across the watershed and down Lid esdale.

NORTH OF ENGLAND.

Dykes. - The Great Whin Sill.

This intrusive sheet can be traced in the carboniferous limestone from Farne Island southward to Burton fell, - a distance of 80 miles. It lies parallel with sedimentary beds with great regularity. Its internal structure, and the wonderful uniformity in its character, mark it out as a typical intrusive sheet. Along its main outcrop the sill dips gently eastwards below the portion of carboniferous limestone which overlies it. Geikie is of opinion that the "sill has been intruded in the carboniferous limestone over an area of 1,000 square miles.

The sill is composed of dolerite and diabase.

It is coarsest in texture where thickest, and finer grained towards its upper and lower surfaces than at the centre.

The main body of the sill is a sheet varying in thickness from 80 - 100 feet. It occasionally divides, as at Great Bavington, where it appears at the surface in two distinct beds separated by shales and limestones. Although it appears to lie parallel with beds above and below, yet in its journey from one end to the other, it passes transgressively across considerable thickness of strata. (Quart. Journ. Geo. Soc. Vol. 32. Topeley and Labour).

The Whin sill appears to thicken in an easterly and north-easterly direction. Where the sill bifurcates. the branches unite towards the east or north-east. This, perhaps, suggests that the sill was intruded from that direction. Another cause, which supports the same conclusion, is that the sill diminishes towards the west, as in Weardale, and finally disappears.

<u>Age</u>. - The sill cuts some of the younger beds of carboniferous limestone series, and so must be younger than those. It has been affected equally by faults which cut the carboniferous beds. It is therefore older than those dislocations. Its striking general parallelism with limestone and shales proves that it was intruded before the rocks were much disturbed from their parallel position. But the manner in which the intrusive rock, when folded, has involved the limestone and shales, seems to indicate that the rock had

already solidified and lay under great pressure. Considering these points, Geikie is of opinion that the intrusion took place sometime late in the carboniferous period. (Anc. Vol. 11. p.8).

<u>Petrography</u>. The prevailing type of rock is distinctly crystalline, (coarse grained) and the general structure sub-ophitic. It is chiefly composed of plagioclase, pyroxene, and titaniferous iron ore. The augite crystals, though somewhat irregular, are twinned, and parallel growth is common. Diallagic laminations are sometimes detected in basal sections. The felspars belong, on the whole, to one generation, porphyritic crystals being absent. The iron-ore is both megnetic and titaniferous, probably an intergrowth of megnetite and ilmenite. Olivine is absent, but its place is

taken up by rhombic pyroxene. It is a green fibrous variety and is probably "Bastite". Though not of common occurrence it is by no means rare.

The specific gravity of the rock varies from 2.9 to 2.98. Analyses by Teall give the following result;-

	1.	11.
$Si\ O_2$	51.22	50.71
$Ti\ O_2$	2.42	1.92
Al_2O_3	14.06	14.78
Fe_2O_3	4.32	3.52
$Fe\ O$	8.73	8.95
$Mn\ O$	0.16	0.31
$Ca\ O$	8.33	8.21
$Mg\ O$	4.42	5.90
K_2O	1.25	1.39
Na_2O	2.55	2.76
H_2O	1.28	1.78
CO_2	0.19	0.25
P_2O_5	0.25	-
$Fe\ S_2$	0.49	-
Total.	99.67	100.48

1. Whin Sill. Cauldron Snout. Durham.

11. Crags near Roman Station of Boargoviens, Northumberland.

DERBYSHIRE TOADSTONE.

For a distance of about 150 miles south of the Great Whin Sill, no carboniferous igneous rock is known to occur. Further south in Derbyshire we meet the "toadstones". Here, by a great anticlinal fold, the carboniferous limestone is brought to the surface. The "toadstones" afford a splendid example of submarine contemporaneous volcanic action. As they occur intercalated amongst the limestone beds, they are exposed only where these limestone coverings have been sufficiently denuded.

Distribution. There are two well-known exposures.

(1) The northern one, which is ~~always~~ also of larger area, spreads from Castleton to Sheldon.

(2) The southern one extends from Winster to Kniveton.

The lavas and sills of these areas have been divided by Mr. Bemrose into three distinct groups:-

(1) <u>Olivine dolerites</u>. These, the most abundant of the series, consist of augite in grains, olivine in idomorphic crystals, plagioclase giving lath-shaped and tabular sections, and magnetite or ilmenite in rods or grains.

(2) <u>Ophitic olivine-dolerites</u>. Consisting of augite in ophitic plates, forming the groundmass, in which are embedded idomorphic olivine, plagioclase, and magnetite or ilmenite.

(3) <u>Olivine basalts</u>. These rocks are distinguished by containing crystals of augite and olivine in a

groundmass of small felspar laths, granular augite and magnetite or ilmenite, with very little interstial matter.

IRELAND.

Carboniferous deposits cover the greater part of the surface of Ireland, and although numerous sections have been laid bare, both by natural and artificial means, it is only in one area, near Limerick, that undoubted contemporaneous igneous rocks have been detected. A second area of doubtful age, however, occurs in King's County. From the absence of more occurrences of igneous rocks, it can be argued that violent igneous actions, which were so conspicuous in Scotland and south-west of England, did not affect the Irish area much during the carboniferous time. It will be seen from the table that Irish eruptions belong to the same periods as those of Scotland and England. In the nature of eruption and

~~and~~ in the nature of the materials erupted, they closely resemble the Puy eruptions of Scotland already described.

1. King's County.

Within an area of a few square miles north of Philipstown, are found small areas of igneous rocks which have been described as composed of "green stone ash" and "greenstone". The chief of these is that which forms Croghan Hill. Piercing through the carboniferous limestone bed, it rises to a height of 769 feet above the level of the sea. It has a diameter of about 4,000 feet, and in general appearance it is very similar to the carboniferous 'necks' of Scotland. Besides Croghan Hill, there are a few, but smaller, 'necks' within the area.

The materials which compose these necks are some remarkable breccias composed of a pale bluish-grey basic pumice fragments about the size of a hazle nut, and occasional fragments of the surrounding limestone cemented together by calcareous material. The breccias, though very similar to those met in carboniferous necks of Scotland, are remarkable in the uniform and homogeneous way they form these necks.

Nowhere the breccias are found stratified and intercalated among the limestone, - a fact which might help to determine their true relation. In the necks, and also through surrounding limestone, masses of eruptive rock have been intruded as irregular bosses and veins. The rocks vary from a deep blue-black, fine grained basalt, to a dolerite where the plagioclase is distinct. Their prevalent structure is amygdaloidal. From a microscopic examination, Prof. Watts found that some of the basalts have a base of felspar and augite, rich in brown mica, and that their porphyritic felspars enclose idiomorphic crystals of augite.

Entangled in the igneous rocks there occurs in the locality of Croghan Demesene, lumps of highly crystalline rocks. They vary from an inch or two to a foot or more in diameter. They must be regarded as blocks which must have been caught and carried up by the ascending basic lava. From a microscopic examination, Prof. Watts found traces of garnet, idocrase, and sillimanite-minerals characteristic of metamorphic sedimentary rocks.

On account of the absence of any direct evidence which may connect the relation of the rocks with one another, Geikie considers the following points in favour of putting the age of these rocks as carboniferous:-

(1) The breccias have no similarity with the Tertiary breccias of Antrim, and so cannot be Tertiary.

(2) They are not likely to be Permian, as there are no known Permian volcanoes in Ireland; nor do they resemble the Permian breccias of Scotland.

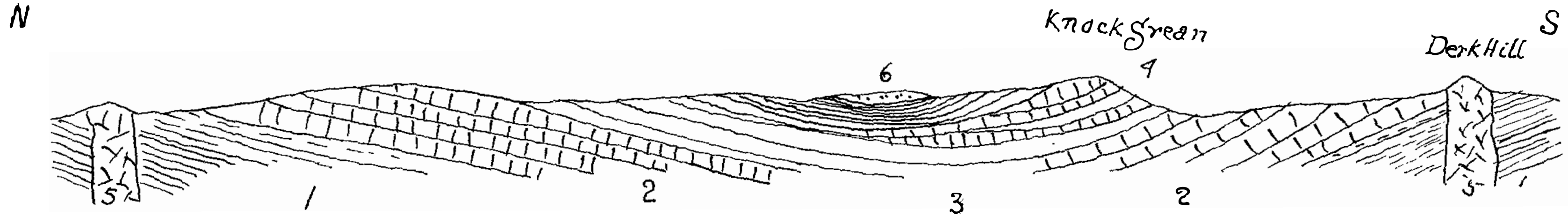
(3) They are more similar than anything else to the carboniferous breccia of Scotland and Derbyshire.

(4) The saturation of the breccias with calcareous material is singular. Considering the thoroughness with which saturation has taken place, it is reasonable to think that the vents could not have been opened long after the formation of limestone beds.

"But if the vents were opened on floor of the carboniferous limestone sea, it is intelligible that much fine calcareous silt should have found its way down among the interstices of the breccia and into the pores of the pumice which, being caked together within the vent, did not float away when the sea gained access to the volcanic funnel. The effect of subsequent percolation would doubtless be to carry the lime into still unfilled crevices, and to impart to the cement a crystalline structure similar to that which has been developed in the ordinary limestone".
(Anc. Vol. Vol. 11. p. 41).

The Limerick Area.

Occurring in an oval basin in the carboniferous limestone series, this area is one of the



1. Lower Limestone; 2 Lower Series of lavas and tuffs; 3. Mid and Upper Limestone; 4 Upper Series of lavas and tuffs

5,5. Two Volcanic necks; 6 Millstone Grit.

most compact, and for its size, most varied and complete of all volcanic districts of Britain. The area, which is near the town of Limerick, is about 12 miles long and 6 miles broad. Within this basin, and enclosing a part of Millstone grit, occurs a second and higher horizon of volcanic outliers of bedded lavas and tuffs. Geikie is of opinion that the original tract must have been 200 to 300 square miles. (See Section)

This volcanic series made its appearance on the floor of carboniferous limestone sea in the same district which had witnessed the eruptions of upper old red sandstone time. This furnishes an excellent instance of recur ence of volcanic energy in the same area after a longer or shorter geological interval. The thickness of strata which separate the carboniferous tuff from those of devonian age is computed by Geikie as 2,000 feet.

The Rowley Hills stretch from Dudley to Rowley Regis, - a distance of about two miles. In places, they have a width of about a mile. The hills occur partly in Worcestershire and partly in South Staffordshire.

The southern extremity of the hills can be reached from Birmingham by G. W. Railway, and is about 7 miles from the City; the northern extremity, which is the town of Dudley, being about 8 miles.

Towards the south, the Rowley Hills seem to end at a point which may be roughly said, to be where the Birmingham road enters the Rowley Regis village. Turning towards N.E., the boundary line seems to pass by the reservoir. It then follows rather a zig-zag northerly course and comes close to the Birmingham-

Wolverhampton Canal, near Rounds Green. (Oldbury). From this point the boundary line turns towards N.W., and can be followed, through Bury Hill Park and numerous quarries, to Kate's Hill in Dudley. From Dudley to Rowley Regis in south, the boundary line runs parallel to Oakham Road. After a short digression at Tanseley Hill, it reappears near Oakham Lodge. Then, coursing south and passing through Rough Hill and Cox Green, it runs further south as far as Ross. From Ross it turns north and comes back to Rowley Regis.

Rowley Hills form one of the links in the chain of high land-marks, which constitute the water-shed of Southern Britain. This watershed divides the basins of the rivers which flow eastwards into the German Ocean from those whose waters run into the Irish

Sea and the Bristol Channel. As the direct consequence of its elevated position, the surrounding country is marked by the absence of any important or navigable river.

Rising in the very heart of the 'Black Country' to a height of about 900′ above the level of the sea, the Rowley Hills command an excellent view of the surrounding country.

On a clear day, looking towards the west, one can clearly see the rounded forms of the Clent Hills merge into an undulating country, beyond which the blue outlines of the Malvern and Abberly Hills close the view. Further to the north, the famous Wrekin, with the Wenlock Edge stretching to the south, and the pall of smoke from the Shropshire iron furnaces, mark the position of a rich industrial district. Turning to the

N.E., the hilly country of N. Staffordshire and Derbyshire bounds the horizon, while towards the east, the elevated summits of Charnwood Forest rise above the surrounding plain. In the south, however, no prominent hills come in view.

Except for the hills of Rowley and those of Dudley Castle, the surrounding ground is rather low and plain-like. Dotted with innumerable chimneys of the factories, the general absence of vegetation, numerous 'coal-tips', and the dirty water-logged clay pits, together with a thick cloud of smoke continuously hanging on the atmosphere, all coalesce in giving the whole surrounding a very dismal appearance.

PHYSICAL STRUCTURE.

A glance at the Geological Map of England shows that the outcrops of the geological formations form sub-parallel bands ranging across the Island in S.W. and N.E. direction. The orderly succession of bands, which have a south-easterly inclination, is twice rudely interrupted by two anticlinal folds. By far the more important of these two anticlines is the one which forms the Penine Chain, and runs from the Scottish border in the north to Derby in the south. This Penine anticline seems to terminate abruptly at the valley of the Trent. Its place, however, is taken up by four other minor anticlinal folds, radiating from the southern extremity of the Penine Chain. Each of these anticlines gives rise to important physical structure in the Midlands.

The first of these anticlines forms the highlands of N. Staffordshire and the Wrekin, and runs as far as South Wales. The second one forms the S. Staffordshire high-lands, the Dudley Hills, the Lickeys, and runs further south, through Worcester, into Gloucester. The third runs through E. Warwickshire, and the last one forms the elevated lands of Charnwood Forest.

The anticline of S. Staffordshire, which ranges ~~from~~ nearly north and south, has lifted up the coal measures, and the post-Triassic denudation has removed the Permian within the coalfields, thus bringing the coal seams, with the accompanying rich bands of iron ore, within the easy reach of miners.

Where the denudation was most severe, not only the overlying Permian has been removed, but also the coal measure exposing the older ~~forms~~ formations from underneath. Most important examples of these exposures are those of Dudley and Walsall, where the rocks of U. Silurian have been brought to the surface.

GEOLOGY.

The oldest formation that is met with within the area is the U. Silurian. Rising in a dome-like form it forms the Dudley Castle Hill. Richly covered with woods from top to bottom, it stands in striking contrast to the surrounding dismal country. The Wenlock or Dudley limestone, which forms the core of the hill, has been denuded at the crest of the anticline, exposing the underlying Wenlock shales. The rich limestone has been mined for centuries, andas the result of pillared excavations, artificial caves of great beauty have been carved out of them.

In S. Staffordshire district, the carboniferous deposits lie directly on the U. Silurian rocks, the old red sandstone being totally absent. The whole range of old red sandstone, which attains tremendous thickness in S. Wales and elsewhere, the carboniferous limestones with its marine fossils, not to say of the millstone grit, - they are all missing; nor is there any evidence that they ever were deposited. (Jukes. Mem. S. Staffordshire. X11).

The carboniferous limestones, with millstone grit, are fully developed in Derbyshire, and can be traced southwards as far as N. Staffordshire, where they seem to thin out and eventually disappear. Again, the same beds are met with in S. Wales. Singularly enough, they too thin out when followed northwards towards the Midlands. So we find that between the thick and thoroughly marine development of carboniferous limestone in Derbyshire and S. Wales there lies a region wherein both the carboniferous limestone and millstone grits die out against a group of Island, or at least a ridge, of elevated land that stretched across from the highlands of Wales through Shropshire, Staffordshire, to Leicestershire. The present heights of Charnwood Forest, the Malvern and the Lickey Hills, seem to mark the position of this ridge. On the slope of this ridge facing N., the limestone is overlapped by millstone grit, which again, in its turn, is found to be overlapped in Staffordshire by the coal measures. That is how we miss the lower and middle carboniferous in S. Staffordshire and the coal measures rest unconformably on the U. Silurian.

It seems probable that during the period while carboniferous limestone and millstone grit were being deposited both in North and in South, amidst general subsidence, this great midland ridge managed to keep itself well out of the surface of water. Towards the beginning of coal measures, however, it went down before the encroaching sea from the north. The coalfield itself is bounded towards the east by the "great eastern boundary fault", ranging from Rugeley through Dudley to the vicinity of Northfield. A similar dislocation known as the 'Great Western fault' bounds the western margin of the field. This runs from the Clent Hills, through Dudley, and Wolverhampton, to Cannock Chase. Both the faults bring down rocks of Permian and New Red age against the coal measures. (See Section. Also Geology of B'ham District p. 365). To the north the coal measures are overlaid unconformably by Triassic ' peeble beds'. It is only in the south that they seem to be followed conformably by Permian 'breccia'.

The coal measure is about 2,000 feet in thickness, and the general succession in the typical part of the coal field is given by Professor Lapworth as follows:-

(2) Upper Coal Measures. 600 - 1,000 feet.

(c) Spirorbis limestone group, - a thin series of red grey and olive-coloured shales, and

(b) Halesowen sandstone group, yellowish and reddish sandstones, with a few thin coal seams.

(a) Red and green coal measure clays with beds of ashy sandstone and conglomerates.

(1) Lower or true coal measures. 600 - 1,000 ft. Grey and white sandstones with shales, clays, ironstone,

and coal seams. Of these the most important are:-

(f)	Brooch Coal	4 feet.
(e)	Thick Coal.	30 "
(d)	Heathen Coal.	3 "
(c)	New Mine Coal.	2 to 11 ft.
(b)	Fireclay bed.	1 to 14 ft.
(a)	Bottom Coal.	5 feet.

IGNEOUS ROCKS.

In association with the coal meeasures of S. Staffordshire occur masses of igneous rock, which on account of their comparative hardness form priminent land-marks within the coal field. Of these, the most important is the 'Rowley Rag'. Those at Barrow Hills, near Dudley, and at Pouk Hills, Nr. Walsall. form other notable instances.

Jukes, in his memoir, mentioned two varieties of igneous rock, namely, 'basalt' and 'greenstone'. A third variety, the 'White Trap', differs from the previous two only in appearance, and its occurrence is limited to the coal seams. This difference, he pointed out, was due to the consolidation of the same molten material under different conditions.

Jukes described the 'Rowley Rag' as a hard, heavy, black, close-grained basalt, produced by sub-agneous or sub-aerial volcanic action, and poured out in the form of a 'sheet of lava'. His reason for calling it a 'lava flow' is "that on the slope of the hill, just below the basalt, there occur some considerable beds of trappean breccia, or brecciated ash, containing rounded and angular fragments of igneous rock lying in a brown, rather ferruginous paste, that looks like the debris of a basaltic rock".

By this 'debris', Jukes presumably meant the brick clay bed which surrounds the 'Rowley Rag', as no other rock of a similar description occurs in the neighbourhood. This brick clay bed has been described by Prof. Lapworth as containing bands of ashy sandstone and conglomerates. These ashy sandstones and conglomerates simulate igneous rock, and considerably so when they are decomposed. It is no wonder that Jukes mistook them for decomposed igneous rock. But careful examination of the rock reveals its sedimentary character.

The ashy sandstone and conglomerates were probably derived from the same volcanic rocks to which the Permian 'breccia' owe their origin. They seem to have been deposited by aqueous action without undergoing much disintegration. In short, they may be described as washed out volcanic rocks. As a result of such a treatment, one can detect a considerable quantity of igneous material in them. The 'greenstones' which Jukes thought as composed of hornblende and orthoclase, are evidently smaller sills made of fine grained basalts. (Watts).

Subsequent observers, who have examined the area, all agree in describing the 'Rowley Rag' as dolerites, intruded in the coal measures. Prof. Watts describes it as a doleritic lac olite "now only in contact with its base, the cover having been totally removed". Later observations, however, have been fruitful in discovering the 'cover' in a few places. To my knowledge, the original discovery is due to the efforts of Mr. Raw, the Lecturer in the University. Mr. Raw has been successful in detecting the junction in a few places. In, at least, three places, I have seen this cover resting on the sheet of dolerite. In all these instances, the cover happens to be the coal measure brick clay.

The first instance occurs in a small and old quarry adjoining, and to the south, of the present Darby's Hill Twin Quarry. (See Map). On the southern side of this quarry, which comes near to the Gipsy Lane, a layer of brick clay about 18 inches to 3 feet in thickness, rests on the dolerite. The face of the quarry is very steep, and at the place, I could with safety, approach, I found the cover composed of sandy material capped by pale coarse-grained and conglomeritic sandstone. This bed is seen capping the dolerite for about a 100 yards along the face of the quarry. Detached pieces of sandstone can be picked up along the foot of the quarry.

The second instance occurs in the old quarry south of the Bury Hil Park, at the point where the

700 contour line cuts the quarry. The exposure is a very small one and runs for about 10 yards. (See Map). Here sandstone occurs in brick red clay, which is about 3 feet in thcikness.

The last exposure occurs in Tansley Hill old quarry. On the northern side of the quarry, and resting on the dolerite, is a thick mass of conglomeratic sandstone. Large detached blocks are now seen lying on the face of the quarry.

From the instances enumerated, it can be argued that Rowley Rag is a laccolite, intruded in the coal measure brick clay.

Similar instances of igneous intrusions occur in other places of South Staffordshire Coal field. The rocks of Pouk Hill, near Walsall, and the rocks of Barrow Hill, west of Dudley, are important examples.

The igneous rocks of the district can be divided into three distinct groups, according to their mode of occurrence:-

(1) Dolerites, which forms large cake-like masses, as at Rowley.

(2) Basalts, which occur as small sills, known as Colliers as "green rocks".

(3) The white traps, which are metamorphosed 'green rocks' by their contact with coal.

(1) Dolerites of Rowley.

The dolerites of Rowley form a big cake-like mass, and, stretching from Dudley to Rowley Regis, have a length of about 2 miles. The breadth, in places, is about a mile. The thickness of the mass cannot be very accurately determined. In Darby's Hill, the face of the quarry is quite 90 to 100 feet in thickness, and I was told by the Manager that there might be another 20 to 25 feet of rock beneath the present level.

The rock is generally massive, although I have picked up specimens along the margin of the mass which show vesicular structure on a small scale. In some cases, the vesicles are filled with secondary minerals, producing, thus, what is known as amygdaloidal structure. In the Darby's Hill, rising from a pool of water, the rock shows a very fine columnar structure. "In Rowley itself, the columns are singularly starch-like, although of very large size". (Watts, Petrology of Birmingham District. p.339)

On weathering, the rock generally developes a very striking spheroidal structure. The spheroids, which are made of concentric shells, are enclosed between more or less rectangular joints, very similar to those as are seen in perlitic structure.

Like most other igneous rocks, the Rowley Rag is traversed by joints. These joints were no doubt produced to ease the horizontal tension developed in the mass during cooling. But where the mass has cooled rapidly at the surface, the vertical strain was only relieved by a kind of exfoliation. This is seen, though roughly produced, in the top portion of the dolerite.

Decomposition. The decomposition of the dolerite has proceeded in a very remarkable way. In many places, the rock 'rots' down to dark brick colour sand, in which are occasionally found more durable spheroids, which, when broken, sometimes show a fresh core, surrounded by a shaly looking ring. Again, there are instances where the dolerite has been totally discoloured into a brownish-yellow mass.

Composition. The main body of the rock is a fine-grained dolerite, containing olivine. Where the mass is thick, specimens from the bottom portion show coarser structure. On some oc asions I have come across very coarse-grained specimens. They are undoubtedly, the products of subsequent injection of molten material in the cracks formed on the solidified rock. The rock have a black to greenish black colour. Samples examined give the following results:-

	1.	11.	111.
SiO_2	49.860	48.8	49.0
Al_2O_3	12.750	18.1	15.3
CaO	8.710	8.4	8.2
MgO	4.395	4.9	4.9
FeO	11.380	7.2	8.2
Fe_2O_3	3.360	3.5	2.6
Na_2O	5.250	3.7	2.5
K_2O	0.570	1.9	2.6
Titanic acid.	1.330	-	2.8
Phospheric acid.	0.580	-	-
Water.	2.560	3.6	3.3
Total.	100.745	100.1	99·4

(1) Dolerite. Mr. Henry. sp. gr. 2.907.

(11) Waller. Mid. Nat. Vol. V111. p.265. The rock contains 2% of titanic acid, which was not estimated in this analysis.

(111) Dolerite Rowley Rag. (J. H. Player).

Petrography. The 'Rowley Rag' dolerite is composed chiefly of augite and felspar. Olivine, however, occurs so frequently that the rock may well be called olivine-dolerite.

The minerals, generally met with, are augite, felspar, olivine, magnetite, ilmenite, and apatite. Zeolites and calcite are sometimes found as secondary products.

Augite. Generally forms idiomorphic crystals, which often show octagonal sections with cleavage lines intersecting nearly at right angles. In tabular section, the angle of extinction is high. (Generally over 30°).

Under the microscope the crystals appear yellowish, pale brown, deep brown, very frequently with a tinge of pink, and, in most cases, slightly pleochroic. Pleochroism is not a general characteristic of normal augites, but it has been suggested that its presence in the augite of Rowley rocks is, perhaps, due to its being titaniferous. This supposition, however, wants verification. It will be noticed that the rock contains about 2 - 3% of Ti O (see analyses). Whether this is derived from augite or mainly from ilmenite present in the rock, or from both, it is impossible to say.

Although the crystals are generally idiomorphic, there are instances where they are found in irregular grains. In Section marked 73 A, coarse dolerite, Hailstone Hill, (Allport's collection, Birmingham University), the augite occurs in large irregular patches, and sometimes includes glassy material. This latter is probably due to the corrosive action of magma on the already formed crystals of augite.

<u>Decomposition</u>. In most cases the augite crystals are fresh. In Section 74 (Allport collection), some of the crystals have been changed into a green substance with the separation of magnetite. This green substance is probably serpentine. In the middle of the same section, there is a blade-shaped crystal, deep green in colour, and showing pleochroism to deeper tints. It gives straight extinction. Along its boundary, and also included within, are grains of magnetite. As this is the only crystal of its nature present in the section, it is difficult to judge the characters with certainty. It is very much like aegerine, but what seems probable is that the crystal, originally a highly ferrugineous

variety of hornblende, has been metamorphosed to its present state by the separation of magnetite. The change in the optical properties might be due to the change in chemical composition.

Felspars. The most prevailing are the plagioclase felspars. Orthoclase is found to a limited extent in the coarser variety of the rock, and also in the contemporaneous veins, to be described later on. The plagioclase felspars seem to be of the labradarite type. They occur both as large untwinned crystals, and long slender crystals, showing polisynthetic twinning. In Section "73 A (Coarse Dolerite, Hailstone") a large untwinned crystal of felspar shows numerous inclusions of apatite needles, which seem to be arranged parallel to the longer axis of the crystal. Besides, inclusions of augite and glassy material are also noticeable. In the same section, some of the felspar crystals are distinctly "schillerized".

In a section from the same locality (74 A), the felspar crystals are untwinned, and may be orthoclase.

Undoubted orthoclase, however, occurs in the contemporaneous veins. Here, the felspars are seen under the microscope to be either simple individuals or binary twins. The striations, so common in plagioclase, are absent. Many of the binary twins extinguish simultaneously, when the trace of the face of composition lies parallel with one of the vibration planes.

Olivine. Occurs as an original constituent. The crystals, whether occurring as phenocrysts or forming the groundmass, are rounded and irregular in shape. In the same section, some of the crystals appear perfectly fresh, and others in different stages of decomposition. (Sec, 71). This clearly shows how irregularly decomposition proceeds in the mass of the rock.

Allport, in describing the British carboniferous dolerites, mentioned five distinct kinds of psendomorphs after olivine, namely, those composed of (a) serpentine, (b) chlorite, or chlorophaeite, (c) hematite, (d) calcite, and (e) zeolite.

Zeolites and calcites certainly do occur in Rowley rocks, but only as secondary minerals, and not as psendomorphs after olivine.

In Section 70, described by Allport as 'Basalt' from Rowley, the larger crystals of olivine have been completely changed into serpentine, and under cross nicols it is clearly visible how this change has taken place along cracks. It seems probable that the change of olivine into serpentine is accompanied by an increase in volume from absorption of water. As a consequence, the crystals are traversed by irregular cracks, along which, as well as from the surface of the crystals, decomposition proceeds to more compact parts.

In Section 74, some of the olivine crystals are seen in different stages of decomposition; some are only partially changed either to a greenish or brownish substance, while others have been completely changed into a deep brown substance. These seem to be psendomorphs of hematite after olivine, as they show pleochroism and have straight extinction.

In most cases the alteration of olivine is accompanied by the separation of iron-oxide, which generally seems to be in the form of grains of magnetite.

The olivine of the Rowley rock is often distinctly coloured in thin section, and evidently belongs to a variety extremely rich in iron. This is further proved by the large amount of magnetic oxide which nearly obscures some of the psendomorphs of serpentine.

Magnetite and Ilmenite. Magnetite is practically a constant constituent of the rock. It occurs both as an original and a secondary mineral. As an original constituent, it sometimes shows well developed octagonal faces. Twinning is sometimes noticed, and takes place along the octahedral face.

When magnetite occurs as a secondary mineral, it is chiefly derived from the decomposition of olivine or augite. Some of the magnetite contains Ti O_2. (Phil. Mag. Nov. 1867, 4th. Series. Vol. 34. pp. 344-346).

In many parts of the rock mass, especially in the coarse-grained rock from Hailstone Hill, beautiful hexagonal crystals of ilmenite occur. The hexagonal tablets are sometimes quite big. In slide 74, some beautiful hexagonal sections are observed. In the same section occur some black rod-like minerals. They may be either ~~horizontal~~ vertical sections of ilmenite, or merely grains of magnetite arranged in a line; Sometimes the ilmenite is seen to decompose into lencoxene, - a grey to whitish looking substance.

<u>Apatite</u>. Occurs in slender hexagonal needles. It is more abundant in the coarser varieties. Under the microscope, the needles are found enclosed in augite and felspar crystals, and also in the glassy base. But Allport noted its absence in olivine.

<u>Glassy Material.</u> is widely distributed in the rock. In some varieties the quantity of glass is quite insignificant. Waller detected some glass in the red contemporaneous veins. Generally, the glass is colourless, although, at times, the different patches are tinged with shades of green. Sometimes, the glassy base shows signs of devitrification. As the result of decomposition, the glass sometimes gives rise to secondary calcite.

ORDER OF CRYSTALLIZATION.

The principal primary constituents of Rowley Rag are felspar, augite, olivine, magnetite, ilmenite, apatite, and a small quantity of glass.

Apatite is found both in augite and felspar, and although never found included in the olivine crystals, it was certainly one of the earliest minerals to crystallize out.

Magnetite and ilmenite, where they occur as primary constituents, were very soon to follow apatite in the order of crystallization. But where the magnetite is of secondary origin, and has been derived from olivine and other ferromagnesian minerals, the order of crystallization was certainly of a later period.

The order of crystallization of felspar and augite in the Rowley Rag is very interesting. Prof. Watts remarks that "this is generally the reverse of that usually found in the dolerites". There are instances, however, where the crystallization appears to have taken place in the normal order, i.e. from basic to acid.

The 'globular aggregates' of Allport is undoubtedly due to the eutectic mixture of augite and felspar where both the minerals crystallized out simultaneously.

So here we have illustrations of:-

(1) Dolerites in which the felspar has preceded the augite.

(2) Dolerites in which the two minerals have crystallized out simultaneously, and

(3) Dolerites in which the felspar has succeeded the augite.

Texture of the Rock. Generally the rock has a crystalline structure, but in some parts it shows a fine, microporphyritic texture. Here, comparatively large crystals of felspar, augite, and olivine are set in a fine granular or micro-crystalline base, composed of the usual constituents.

A very interesting example is afforded by the rock at Tanseley Hill, near Dudley. The prophyritic constituents are felspar, and, occasionally, olivine, but they can only be recognised under the microscope. The groundmass, which makes up the greater portion of the rock, is an aggregate of extremely minute augite crystals, magnetite, rods of ilmenite and felspar.

The felspar, which practically forms the groundmass, shows, in a few places, "most characteristic signs of the mass having been in motion after they were formed. They lie in streams, their lengths being to a good extent parallel to each other". (Waller, Mid. Nat).

The interesting part of Tanseley Hill rock, as Teall points out, is, that this type of rock is not known in the Tertiary basalts of Brito-Icelandic province, but is extremely common in the Tertiary basalts of the Continent. (e.g. Bohemian basalts). (British Petrography. Notes on plates 24 fig. 2).

In some of the coarsely crystalline patches of the rock, Mr. Allport observed a remarkable intergrowth of felspar and augite, which he described as 'globular aggregation'. In one part of slide No. 74

of his collection, a crystal of felspar is seen to contain a fairly large grain of augite. Smaller grains of augite, however, are seen to radiate from the larger crystal. On using the analyser, all the augite crystals are seen to extinguish simultaneously, which simply proves that they form parts of one and the same crystal. It may be mentioned here that this texture is better known as '*micro-pegmatitic*', on account of its frequent occurrence in the pegmatites.

THE GREENSTONE AND THE WHITE TRAP.

The sheets of "greenstone" met with in the coal field are more numerous and extensive than the detached areas of more compact rock visible above ground, a single sheet being sometimes traceable in the coal workings for quite two miles in one direction. They were described by Jukes as composed of orthoclase and hornblende. Prof. Watts considers them as smaller sills of fine grained basalts. When found away from the coal, they are usually green and appear to be more decomposed than the Rowley Rag. Their green colour is, in most cases, due to the decomposition products, e.g. chlorite and chlorophaecite.

In the neighbourhood of coal, the sills become lighter in colour, and even white when they occur intersecting the coal seams. The rock thus changed was described by Jukes as the 'white trap'.

An analysis of the trap is given in Jukes's memoir with the following result:-

SiO_2	38,830
Al_2O_3	13,260
CaO	3,920
MgO	4,180
Na_2O	0,971
K_2O	0,422
FeO	13,830
Fe_2O_3	4,330
CO_2	9,320
H_2O	11,010
	100,073

The high percentage of carbonic acid and water suggests a great alteration in the original rock. By deducting the combined proportions of these two constituents, and reducing the remainder to percentages, Jukes got the following result:-

SiO_2		48.8
Al_2O_3	16.7	22.1
Fe_2O_3	5.4	
CaO	4.8	29.0
MgO	5.2	
Na_2O	1.2	
FeO	17.3	
		99.9

which suggests that the original rock was possibly very similar to Rowley Rag. This suggestion is further supported by the close relation which the 'traps' bear to the rocks of Rowley and Pouk Hill. At Deepmore Colliery, Near Walsall, the 'green rock' is found in the "bottom coal", which is burnt. Specimens taken from the least altered parts of the 'green rock' show but lit le change. Under the microscope such a specimen is seen as composed of nearly or quite unchanged augite, plagioclase, magnetite, apatite, and interstitial glass. Olivine is represented by psendomorphs of delessite, or chlorophaeite and chlorite. (Allport. Q.J.G.S. 1874. p.549). Where the rock shows amygdaloidal structure, the amygdules are chiefly composed of fibrous zeolites and calcite.

As the rock approaches the coal, it is found to become lighter in colour, and, near the junction, nearly white.

In the 'white trap' itself, the alteration is so complete that the constituents have been totally decomposed, but their forms are so well preserved that they can be easily recognised under the microscope. Curiously enough, the only mineral which has suffered least from the decomposition is felspar, some crystals of which are seen to be singularly fresh.

Allport thought that the alteration of the rock consisted "chiefly in the decomposition of the ferruginous silicates". The white colour of the trap is attributed by Teall to be due to 'the fact that carbonaceous matter of the coal has prevented the oxidation of the iron'.

Contemporaneous Veins.

Within a few yards of the coarsely crystalline masses, Allport discovered some red veins in the black dolerite, which he described as contemporaneous injections. They can be traced for several yards across the joints in the rocks, but have no ulterior ends. The constituents of the veins are more coarsely crystalline than those of the surrounding rock. The veins have generally a greyish colour, but are sometimes red; the red colour being due to fibrous zeolites.

A sample analysed by Mr. Waller gave the following result:-

sp. gr. - 2.58.

SiO_2	58.3
Al_2O_3	17.9
Fe_2O_3	2.5
FeO	3.0
CaO	2.1
MgO	1.9
Na_2O	5.2
K_2O	5.9
H_2O	2.7
	99.5

It is interesting to note that the rock has a slightly lower specific gravity than the Rowley Rag, and contains more silica, less iron, lime and magnesia, more alkali, and relatively more potash. (See analysis of Rowley Dolerite). In short, the rock is decidedly more acid in composition than the surrounding rock.

Under the microscope, the vein is seen to be composed of beautifully clear and fresh crystals of felspar. They mostly show carlsbad type of twin ing and polysynthetic twinning is totally absent. Besides, carefully selected twin crystals give straight extinction, which proves that the felspar is orthoclase. This inference is in conformity with the high percentage of potash present in the rock. (See analysis). The angular spaces between the felspar crystals are filled with glassy base. "In a few places, this has a stringy, uneven look, coming near to Rosenbuch's microfelsite, and, in others, there is a very faint and vague polarization, evidently due, in some cases, to very fine films of felspar; but in others to a quite decided cryptocrystalline character". (Waller, Mid. Nat. Vol. viii).

In rock slide No. 70, (Contemporaneous Vein, Rowley) augite occurs but sparingly. It has a green colour instead of the usual brown colour of those in the normal rock. The vein itself has a reddish colour owing to the presence of a large quantity of fibrous zeolites. The zeolites are, of course, of secondary origin, derived most probably from the decomposition of felspar and the glass.

The mode of occurrence of these veins led Allport to suggest that they were contemporaneous, formed, perhaps, by the injection of fluid mass in the cracks of partially cooled magma,

It may be pointed out that here we have an instance of magnetic differentiation. Waller suggested that the vein staff may possibly be the more acid parts left after the separation of a certain amount of crystals from andesite (?) magma, the separation having been effected either by the subsidence of the crystals or by the still fluid residuum being squeezed out from among them, "as water from a sponge".

That the differentiation of the magma took place, at least, before the felspars crystallized out, is pproved by the fact that we find two different sorts of felspars in the products of differentiation, - plagioclase in the normal rock and orthoclase in the vein. Had the crystallization taken place prior to differentiation, we should have expected to find the same felspar in both the products.

The Age of the Intrusion.

Rocks similar to Rowley Ragg occur in other parts of the Midlands. In all cases, except one, they are found intruded in upper coal measures. At Swinnerton Park, a mass of dolerite, very similar to the Rowley Rag, has been proved by Kirkby to be of Post-Triassic age. Mr. Kirkby, while proving its intrusion in Triassic rock, suggested that it might be connected with S. Staffordshire igneous rocks. (Trans. N. Staffordshire Nat. Field Club. Vol. 28, 1894, p129).

On this assumption all the rocks belong to Post-Triassic age. Geikie, however, refuses to accept Kirkby's suggestion, as there is no substantial evidence,to support it. (Anc. Volcanoes, Vol. 11. p.106.

Jukes, in his memoir, puts the age of Rowley Rag as pre-permian. He pointed out that, in the surrouhding district, "no igneous rocks of any kind are found in any formation, newer than the coal measures". He further argued that "at whatever period these igneous rocks were produced, they were all existent before the production of the faults, and before any great denudation had been affected on the country".

It may be mentioned here that a great number of these faults cut through Permian and Triassic rocks.

A few even cut the Juras ic strata, so that igneous rocks protruded during those periods would be affected by the same dislocations.

In support of Jukes's view, it may be mentioned that the general trend of the dislocations, which have affected the igneous rocks in S. Staffordshire, is the same as of those which affect the carboniferous dolerites of Scotland.

Geikie puts the age of these rocks as Permian. He argues that "though the dolerite sills and veins are so abundant in S. Staffordshire coal field, coming, in many places, up to the present surface of the ground, no single case has been observed where they rise into the Permian rocks that overlie the coal measures unconformably. It is difficult to believe, that had these intrusions taken place after the deposition of the younger formation, they should not be found penetrating it". (Anc. Vol. Vol. 11, p.106). His chief argument in support of his statement, is that the proof obtainable from the Palaeozoic history of Britain shows a general quiescence in the volcanic activity during the Upper Carboniferous time. "And as there is clear evidence of contemporaneous volcanic action in the lowest portion of the Permian system to the north in Scotland, and to the south in Devonshire, it is quite possible that the rocks of the Midlands belong to Permian too".

The striking resemblance in petrographical characters which the Rowley dolerites bear to those of Antrim and other places, has led Prof. Watts to suggest that the intrusion is of Tertiary period. While admitting the great similarity betwe n the two types as regards the "colour and pleochroism of augite and the inconstant relation of the chief constituents", it is difficult to assign the age of a rock chiefly on petrological grounds. Besides, one has to remember that according to modern petrography 'the recurrence of the same types in different regions and at different geological periods', (Harker, Igneous Rocks. pp. 366 - 367) is quite conceivable,

It appears then, that considering all possible arguments, it is natural to put the age at Permian, as Giekie's arguments certainly seem most weighty.

THE EFFECTS OF METAMORPHISM.

The effects of metamorphism on the rocks of the district may be enumerated as:-

(a) On the coal.

(b) On the igneous rock, and

(c) On the brick clay.

(a) <u>The effect of igneous rock on coal</u>. The thick coal has been worked all round the Rowley Hills. Shafts have been sunk piercing the dolerite, to the workable seams of coal below. The effect of igneous rock on the coal, where it comes in contact with it, was noted by Jukes. He pointed out that in every case of such an contact the coal appeared to have 'blacked'. "A coal is said to be 'blacked' when, by its proximity to an igneous rock, it has become so altered so as to loose all its brightness, and nearly, if not quite, all its inflammability. It is not exactly coke, but is dull and earthy, and on exposure to the atmosphere is very friable".

(b) The effect on the igneous rock itself when it comes in contact with coal has already been mentioned. (p. 209) The green sills become lighter in colour as they approach the coal, and at the point of contact become nearly white. The metamorphosed igneous rock is known as the 'White trap'.

(c) The brick clay bed practically surrounds the Rowle Hills. There are a few exposures where they are found to come in direct contact with the igneous rocks. (p. 186). For reasons mentioned on (p. 185) the effects of intrusion of the igneous mass in the brick clay is but very slight. At most the rocks become sandy or ashy with a deep red or brown colour, - effects which suggest a slight burning or baking.

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