

Basaltic formation of Ulster" ('Q. J. G. S.,' Vol. xli, 1885, p. 82) for further details. The beds are chiefly of the age of the Heersien beds of Belgium, which, as I have elsewhere attempted to show,\* are of the same age as the lower part of our Thanet beds. We may look forward with interest to the further investigation of these Irish and Scotch Eocenes.

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### ORDINARY MEETING.

FRIDAY, APRIL 1ST, 1887.

F. W. RUDLER, F.G.S., Hon. Sec. Anthropol. Inst., President,  
in the Chair.

The donations to the Library since the previous meeting were announced, and the thanks of the Association accorded to the various donors.

The following were elected Members of the Association:—

Captain W. Ashby; A. Cates; J. W. Dale; H. G. Erith;  
Rev. E. Hill, M.A., F.G.S.; H. E. Jones; H. W. Sich.

The following paper was then read:—

'On the metamorphosis of basic igneous rocks.' By J. J. H. Teall, M.A., F.G.S.

The paper was illustrated by lantern slides (many of which were photographs taken by Mr. Barrow) and by hand specimens.

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### THE METAMORPHOSIS OF BASIC IGNEOUS ROCKS.

BY J. J. HARRIS TEALL, M.A., F.G.S.

An igneous rock may be said to attain individuality at the time of final consolidation. Many minerals which enter into its composition may have been formed previously, but the birth-time, so to speak, of the rock is the time when the last portions of molten matter solidify. So long as the rock remains subject to the conditions which prevailed at the moment of final consolidation, it is in a state of stable equilibrium. These conditions do not, however, remain constant, as a rule, for any considerable length of time, and accordingly we find that the rock in adapting itself to the changed conditions, or, in other words, in adapting itself to its environment, undergoes important modifications in structure and composition. As we examine it, the rock is not in its original condition; it has been more or less metamorphosed.

\* 'Geol. Mag.,' Dec. 3, Vol. iv (1887), p. 108.

The principal mineralogical constituents of the basic igneous rocks are certain anhydrous silicates of complex composition. When subjected to the low temperatures and pressures which prevail at the surface, and to the chemical action of air, water, and carbonic acid, these silicates are in a state of unstable equilibrium, Their molecular structure breaks down, and the chemical elements rearrange themselves, in accordance with the new set of chemical affinities, so as to form compounds which are more stable under the existing circumstances. In this way, silica in various forms, carbonates, iron ores, and various hydrated silicates, such as kaolin, chlorite, and serpentine, are produced. The extent to which a basic igneous rock may be modified by these agencies—the surface agencies as they may be conveniently called—varies within wide limits. It may be so slight as not to interfere seriously with the individuality of the rock, or it may be so great as to completely destroy this individuality. The soluble constituents may be so removed that a pulverulent mass, mainly composed of hydrated silicate of alumina, alone remains to attest the former presence of the igneous rock ; or, under suitable conditions, even this may be carried away mechanically, and the solid rock may disappear.

The metamorphosis of basic igneous by surface agencies has long been so well understood that it is no part of my purpose to treat it at any length in this communication. Another and a very different type of metamorphosis is that dependent upon actions which take place beneath the surface. This is much more difficult to study because the operations go on out of sight, and our information with regard to them is therefore mainly derived from an examination of the effects long after they have been produced. Two different kinds of metamorphism dependent upon actions going on beneath the surface are at present recognized : the principal agent in the one case is an elevated temperature acting under what may be called normal conditions of pressure, that is, under such pressure as is naturally due to the weight of the overlying material ; the principal agent in the other case is the mechanical energy which results in the folding, crumpling, and faulting of the rocks. The effects of these two more or less distinct kinds of metamorphism are often superposed. What is generally known as contact metamorphism may be mentioned as an illustration of the first kind. Messrs. Allport\* and Phillips† have familiarized us

\* 'Quart. Journ. Geol. Soc.,' Vol. xxxii, p. 407.

† 'Quart. Journ. Geol. Soc.,' Vol. xxxii, p. 155, and Vol. xxxiv, p. 471.

with the effects of the intrusion of masses of granite upon igneous rocks of basic composition. They have shown that the augite becomes replaced by secondary hornblende, which usually takes the form of uralite or actinolite; that the felspar also undergoes modification; that a pale brown mica is very frequently developed; and that, occasionally, such minerals as axinite, tourmaline, and garnet make their appearance. Lossen has shown that precisely similar results have been produced in the Hartz.

My principal object in this communication, however, is to call attention to the second kind of deep-seated metamorphism, the significance of which we are only beginning to recognize, and most of the details of which yet remain to be worked out. This is generally referred to as dislocation, or regional-metamorphism. It has also been termed pressure-metamorphism, and although certain objections may be taken to this expression, it is a very convenient one to use, and no serious harm will result if we form our ideas as to what is meant by a consideration of the facts rather than by dwelling on what may or may not be indicated by the term itself.

Nothing is better understood by the geologist than the fact that the rocks of the earth's crust have, in certain places, been deformed (strained) by mechanical stresses. We are not agreed at present as to the way in which these stresses have been produced, but, for our present purpose, this is a matter of no consequence. Now, the deformation of a solid mass may take place in two, more or less distinct, ways. It (the solid mass) may crack along certain planes, and the different fragments may slide along these planes. This may be termed deformation by faulting.\* Or the deformation may take place by an interstitial movement of the constituents without the formation of actual cracks. This may be termed plastic deformation, or deformation by interstitial movement. A deformation of the latter kind takes place in molten masses erupted at the surface of the earth. Suppose a mass of viscous lava, not entirely homogeneous (say a mass of rhyolite), to be erupted in a boss or lump, and suppose it to be deformed by gravitation into a flat sheet, the resulting mass will show banded and fluxion structures, and the bands will lie approximately parallel to the fixed surfaces which determined the character of the deformation. In the plastic deformation of solid masses precisely similar structures arise.

\* Good illustrations of this type may be found in almost any district. It is admirably illustrated on a small scale by the faulted slates of the Lake District.

The two types of deformation are not separated by any hard and fast lines. Deformation by faulting may pass into plastic deformation by a diminution in the distances between the different dislocation planes. These may become at last so small as to affect only the individual constituents of the rock. Plastic deformation is, however, usually accompanied by molecular changes; the old minerals are destroyed, and new minerals are formed. In this respect there is a more decided difference between deformation by faulting and deformation by interstitial movement. Nevertheless, it must be remembered that even here the difference is not absolute. Mineral changes often take place along definite planes of movement.

So far, I have endeavoured to sketch in general outline the main features of what may be termed the modern theory of regional metamorphism, a theory which has been mainly developed, in its general aspects, by Lossen,\* Heim,† and Lehmann‡. I propose now to apply this theory to the basic igneous rocks, selecting as examples various British rocks which have been examined by myself and others. These rocks are especially useful in determining the structural and mineralogical changes accompanying this type of metamorphism, because we are tolerably familiar with their original structure and composition. Before proceeding to consider the changes in the rocks themselves, it will be necessary to treat briefly of the changes in the different constituents. Regional metamorphism often takes effect on rocks that have been more or less modified by other agencies, so that in dealing with this portion of the subject we shall not limit ourselves entirely to the effects of one type of metamorphism. Indeed, it is very often impossible to separate the effects of different kinds of metamorphism. The essential constituents of basic igneous rocks have already been mentioned. One of the most important accessories is olivine, and we must accordingly add this mineral to our previous list.

**PLAGIOCLASE.**—The dominant felspar of the basic igneous rocks is labradorite, or bytownite. The synthetic experiments of Messrs. Fouqué and Lévy make it highly probable that the ophitic structure, so common in this group, is dependent on the presence

\* "Studien an Metamorphen Eruptiv-und Sediment-gesteinen." 'Jahr. k. Preuss. Geol. Landesanstalt für 1883.' Berlin. References to numerous earlier papers by the same author will be found in this communication.

† 'Mechanismus der Gebirgsbildung.' Basel, 1878. 2 Bde. and Atlas.

‡ 'Die Entstehung der alt-krystallinischen Schiefer-Gesteine.' Bonn, 1884.

of a basic feldspar. These experimenters found that the structure could easily be produced with anorthite and augite, and less easily with labradorite and augite. It has never been produced, so far as I know, with oligoclase and augite.

In the granitic rocks of basic composition (*i.e.*, in the gabbros) the feldspars give sections having tolerably uniform dimensions in the different directions. In the medium-grained rocks (dolerites) they give lath-shaped sections of considerable dimensions, and in some cases are present also in well-formed porphyritic crystals. In the fine-grained and compact rocks (basalts) they often sink to microlitic dimensions. They almost always show twinning on the albite plan, and less frequently twinning on the pericline and Carlsbad plans. As it is difficult to trace the various stages of metamorphism in the fine-grained and compact rocks, we shall not refer to them at any length in what follows.

The feldspars of the gabbros in regional-metamorphic areas present features not known in the corresponding rocks of undisturbed districts. In both, we may find evidence of strain as shown by undulose extinction, and the bending of twin lamellæ, but this is much more marked in the disturbed than in the undisturbed areas. A feature which, so far as we know at present, is limited to the gabbros of disturbed areas, is the partial or complete replacement of the original feldspar by a water-clear mosaic of small grains, for the most part devoid of twin striation. The connection between the development of the mosaic and the straining of the original mineral is admirably illustrated in some of the Lizard gabbros. A plane of strain, where it crosses the feldspar crystal, is often marked out by a narrow band in which the mosaic structure has been developed. The other parts of the crystal may exhibit merely a bending of the lamellæ. From such a case we may pass by a regular gradation to others, in which the original grain has been entirely replaced by a feldspar mosaic.\* Cases of the replacement of the original plagioclase of the dolerites, or diabases, by a similar mosaic have been described by Lossen. An important question arises as to the nature of the water-clear secondary feldspar. According to Lossen it is in many cases albite. Now, the development of albite at the expense of labradorite involves the separation of lime. This is probably in some cases removed altogether. In others,

\* The formation of a mosaic in connection with regional metamorphism appears to be a very common feature. It may be seen in the quartz and feldspar of the intermediate and acid rocks.

it remains behind as calcite, or in such minerals as zoisite and epidote. Cathrein's researches on the nature of certain so-called saussurites became of great importance in this connection. This observer proved that many saussurites are mixtures of albite and zoisite. A similar aggregate occurs at Sango Bay, near Durness. I am indebted to Prof. Lapworth for the loan of some very fine examples of zoisite-bearing amphibolite from Ben Hutig in Sutherlandshire. It must not be supposed, however, that all substances to which the term saussurite is applied possess the same composition. Thus the so-called saussurite of the Lizard is often composed of feldspar, malacolite, an unknown substance, which is white by reflected, and brown by transmitted light, and minute granules of sphene.

Mr. Adams\* has shown that the feldspars of certain actinolitic schists occurring in the Quebec group are rich in soda, and therefore in all probability albite. We must not, however, regard it as proved that the secondary feldspar is in all cases albite. Veins of andesine occur in the Scourie dyke,† and there is no reason why the same mineral should not have been developed in the rocks. The balance of evidence at present appears to be in favour of the view that the secondary feldspar is in general more acid than the original feldspar.

Doubt may exist in the minds of some as to whether a secondary feldspar is really developed in connection with the metamorphism of basic igneous rocks. On this point the evidence seems to me satisfactory. In many cases it is quite easy to distinguish between the two feldspars. Thus in the Scourie dyke the original feldspar is somewhat turbid. It gives lath-shaped sections, and is entirely free from all inclusions of the ferro-magnesian constituents. The secondary feldspar is water-clear. It occurs in irregular grains, and frequently contains inclusions of hornblende.

**PYROXENE.**—The monoclinic pyroxene of the gabbros is usually diallage; that of the dolerites, augite. Both forms disappear in the process of metamorphism, and their places are taken by hornblende. The secondary hornblende may be uralitic, actinolitic, or "compact." It is said to be uralitic when it is fibrous, and retains more or less of the form of the original mineral. Sections of uralitic hornblende give fairly uniform but not perfectly definite extinction. The absence of definiteness in the extinction is, of course,

\* 'Report of Canadian Geol. Survey for 1882.'

† 'Quart. Journ. Geol. Soc.,' Vol. xli, 1885, p. 133.

due to the fact that the axes of the fibres are not rigidly parallel. The hornblende is said to be actinolitic when it occurs in the form of long needle like prisms, having definite crystalline outline in the prismatic zone. In the hornblendic gabbros or gabbro-diorites, a fringe of actinolite may often be seen surrounding a mass of uralite. Actinolitic hornblende frequently occurs as inclusions in the water-clear secondary felspar. When the hornblende consists of grains or crystals having perfectly definite cleavage and uniform optic characters, it is said to be "compact." Secondary hornblende of all kinds is usually green. Brown tints may, however, be occasionally observed.

What relation does the secondary hornblende bear to the original augite, so far as chemical composition is concerned? This is a question we are unfortunately unable to answer with any degree of definiteness. We know from the researches of Gustave Rose, Fouqué and Lévy, and others, that augite will crystallize out of a fused mass of hornblende, but this, of course, does not necessarily prove that the two minerals are identical in composition.

We want a series of analyses of the original augite and the secondary hornblende from several different rocks. In considering the relations of the two minerals, it is of the utmost importance to remember, as Mr. Williams\* points out, that hornblende is much more stable at low temperatures and pressures than augite. Augite is eminently characteristic of true igneous products; hornblende, and especially green hornblende, is more characteristic of the crystalline schists.† Augite has frequently been produced synthetically; hornblende has never been so produced.

Augite and hornblende develop chloritic products when subjected to alteration by surface agencies. Rhombic pyroxenes occur in some of the basic igneous rocks, and Mr. Williams has shown that they give rise to hornblende very much in the same way as augite or diallage. Surface alteration produces bastite and ultimately serpentine.

OLIVINE.—This mineral may or may not occur. Where it does occur it appears, as Prof. Bonney long ago pointed out, to give rise to hornblende. When affected by percolating waters, it produces

\* "On the Paramorphosis of Pyroxene to Hornblende in Rocks." *Amer. Journ. Sci.*, Vol. xxviii, p. 259.

† Augite occurs abundantly in certain portions of the Hebridean gneissic system, in association with plagioclase and quartz. The rocks in question may be termed augite or diallage-gneisses. They are the gneissic equivalents of the quartz-gabbros or augite-diorites.

serpentine, and the change is often accompanied by the separation of iron oxides. The olivines of gabbros are sometimes surrounded by zones of other minerals, such as enstatite, anthophyllite, and actinolite. Prof. Rosenbusch\* holds that zones of anthophyllite and actinolite, such as occur round the olivines of the gabbros of Rosswein and the Lizard, are developed in connection with pressure metamorphism. Mr. Adams† holds that the zones of pyroxene and actinolite, which surround the olivines in certain gabbros of the Saguenay river in Canada, are original. Mr. Williams‡ is of the same opinion as regards the rocks of the Cortlandt series.

**TITANIFEROUS IRON ORES.**—These minerals are eminently characteristic of the dolerites. They are of great interest in connection with metamorphism, because their presence will frequently give a clue to the origin of a foliated rock in which almost all traces of the original structure and composition have disappeared. In one special type of dolerite or diabase, very commonly found associated with the palæozoic rocks of the West of England, Wales, and Ireland, the iron ores take the form of plates of ilmenite, arranged in parallel rows, and intersecting at angles of  $60^{\circ}$ . Sometimes the spaces between the different plates are filled up, possibly with magnetite, and then the reticulate structure can only be recognized after a certain amount of alteration has taken place, or by etching the slide with acid. The characteristic alteration product of ilmenite and titaniferous magnetite is leucoxene, a substance which has been proved by Cathrein to possess the composition of sphene. In some cases the leucoxene of the diabases is partially transparent, and when this is the case it possesses the refraction and double refraction of sphene.

When a diabase with ilmenite is subjected to plastic deformation, the ilmenite often retains its character better than either the felspar or augite. Many of the "schistose greenstones" of Cornwall may be thus shown to be metamorphosed diabases, although the original augite and felspar have entirely disappeared. Plastic deformation does, however, in the end affect the ilmenite. The ragged plates and skeletons become dragged out in the plane of schistosity, and more or less replaced by minute vividly polarizing granules of sphene. In the end the ilmenite disappears, and its presence is then only indicated by long streams of sphene granules.

\* 'Mikroskopische Physiographie,' &c. 2nd edition, p. 413.

† 'American Naturalist,' 1885, p. 1087.

‡ 'Amer. Journ. Science,' Vol. xxxi, p. 35.



Many hornblende-schists contain rutile, and it is quite possible that this mineral may owe its origin to the separation of titanic acid in connection with the metamorphosis of iron ores.

Having passed in review the more important mineralogical constituents we proceed to consider the rocks themselves. Many observers have held the view that hornblende-schists are metamorphosed igneous rocks. One of the earliest of these appears to have been the late Prof. Jukes. Mr. Allport in his classic paper on "The Metamorphic Rocks surrounding the Land's End mass of granite," suggests that "hornblende-schists may be metamorphosed igneous rocks, some being derived from dolerites or gabbros, while others are very probably foliated diorites." Mr. John Arthur Phillips, whose loss we so deeply deplore, not only realized that a foliated schist might be produced by the metamorphosis of a massive rock, but also clearly indicated the manner in which the change is brought about. He states that on St. Cleer Down "the hornblende slates graduate imperceptibly from crystalline dolerite on the one hand, into clay slates on the other; and instances are by no means wanting where a rock is massive and crystalline near the centre of its outcrop, while externally it is schistose and without visible crystals." He attributes the development of the schistose structure to the cause which produced the slaty cleavage in the sedimentary beds. Precisely similar conclusions were arrived at by Lossen from his study of the rocks of the Hartz.

The more recent work of Reusch in the Bergen peninsula,\* of Lehmann in the granulitic region of Saxony, and of Lapworth and the Geological Survey in the Highlands of Scotland, have brought strongly into prominence the immense importance of mechanical deformation in relation to the problem of the origin of the crystalline schists. Extensive districts composed of diverse rocks have been so profoundly modified by the earth-stresses that their original structural planes have almost entirely disappeared, and new structural planes have been produced which stand in direct relation to the earth movements. This change has sometimes been accompanied by a crushing, and sometimes by a molecular rearrangement of the original constituents. We will now see how these ideas help us to understand certain facts with regard to basic igneous rocks.

Consider first of all the holocrystalline rocks of medium grain—the dolerites of Mr. Allport, the diabases of continental authors.

\* 'Die fossilien fuhrenden krystallinischen Schiefer von Bergen.' Leipzig. 1883.

These rocks are essentially composed of a basic plagioclase, augite and magnetite or ilmenite. One very common type of structure is the ophitic. This structure depends on the fact that the augite crystallized after the felspar; augite therefore plays the rôle of ground mass. The ophitic structure occurs in rocks of all ages, and has been reproduced artificially by Messrs. Fouqué and Lévy. It is a characteristic igneous structure. Now when we find, in regions which give independent evidence of having been subjected to dislocation-metamorphism, and in these regions alone, that ophitic dolerites pass over into hornblendic and chloritic schists, we are, it seems to me, justified in concluding that the schists in question are due to the metamorphosis of the dolerites. Let us consider illustrations of this.

The Hebridean gneissic system of Sutherland is cut by basic dykes of plagioclase-augite rock. Their general trend is N.W. and S.E. One of these dykes near the village of Scourie passes over in places into a typical hornblende schist. There is no marked difference in chemical composition between the schist and the original rock. The original rock is composed essentially of plagioclase, augite, and magnetite or ilmenite. The plagioclase is generally more or less turbid in consequence of alteration. It is twinned in the usual way, and gives lath-shaped sections. The augite is pale in colour, and, as a rule, without definite form. It is often penetrated by the felspar, and has in such cases crystallized after that mineral. In some cases the augite contains one or more planes of inclusions, and when this is the case it must be termed diallage or pseudo-hypersthene. These inclusions are of some importance, because they may occasionally be seen in the secondary hornblende. The iron ores are present in the form of irregular grains or skeletons made up of plates intersecting at angles of  $60^{\circ}$ . Apatite occurs sparingly.

This rock has in some places undergone complete or nearly complete molecular rearrangement without the development of foliation; in other cases a most perfect foliation has been produced. The gradual replacement of the pale augite or diallage by green hornblende is admirably illustrated. Sometimes the augite is merely fringed with hornblende, at other times only a ragged core of augite is preserved, at others no augite remains. The hornblende may be fibrous, actinolitic, or compact. Very often it is completely honeycombed, as it were, by little granules of a colourless mineral which is presumably quartz.

This feature is described by Williams in his communication on the Baltimore gabbros,\* and is well illustrated in one of his figures. The replacement of augite by hornblende is accompanied by modifications in the felspar. The original felspars became replaced by an aggregate of irregular water-clear grains.

Actinolitic hornblende is frequently present in these grains as inclusions, a fact which seems to prove their secondary character. Twinning is much less common in the secondary than in the original felspar. We have no direct evidence as to the nature of this felspar. Veins of andesine, certainly of secondary formation, occur in the dyke at a point where it has been greatly strained, and it is very probable that the same felspar has been generated in the rock-mass. The iron ores in the altered rocks are often associated with minute vividly polarizing granules of sphene.

The molecular changes above referred to are sometimes accompanied by the development of the most perfect foliation. The transition from the massive to the foliated portions is gradual, and may occur in the space of an inch or less. The resulting schist is perfectly typical. In a schist, as in a slate, there are three directions at right angles to each other which should always be noted. There is first the direction normal to the plane of schistosity; there is, secondly, the direction of stretching, as the Germans call it—that is, the direction in the plane of schistosity in which deformed particles are elongated; and, lastly, there is a third direction, also in the plane of schistosity, at right angles to the other two. These three directions correspond to the three axes of the ellipsoid of deformation (the strain ellipsoid) in a slate. In studying schists and slates it is desirable, if possible to prepare sections at right angles to each of the above directions. In the hornblende schist of the Scourie dyke these directions are indicated by a rude kind of orientation in the hornblende grains, and by the manner in which the ilmenite has been deformed.

The principal constituents of the schist are green hornblende, felspar, iron ores, sphene, and some quartz. The hornblende occurs in the form of irregular grains, which are, as a rule, slightly elongated in the direction of the vertical axis.

The felspar, in the most perfect schist, occurs in the form of

\* 'Bulletin of the U.S. Geol. Survey,' No. 28.

colourless grains. In the less perfect schists a certain amount of turbid felspar is usually present. The iron ores occur as elongated lenticles lying in the plane of schistosity. They are usually bordered by minute granules of sphene, and sometimes a long streak of iron ore may be seen to tail off in a row of such granules. Broken prisms of apatite may occasionally be recognized. Quartz occurs, but is by no means easy to distinguish from the water-clear, untwinned, secondary felspar. The most important methods of discrimination are those which depend on the use of convergent light. Quartz is, of course, uniaxial.

Let us now turn to the West of England. The basic igneous rocks of this district—the so-called greenstones—are of exceptional interest on account of the extent to which they have been metamorphosed by the Post-Carboniferous earth-movements, and by the intrusion of large masses of granite. Devon and Cornwall, together with Brittany, constitute a part of an old chain of highlands which formed a marked feature in the physical geography of northern Europe during Mesozoic times. The Devonian-Carboniferous and Pre-Devonian rocks, of which this chain was composed, are concealed at intervals by Mesozoic and Tertiary strata, but wherever they come to the surface, as is the case in the Ardennes, the Eifel, Westphalia, Thuringia, and the Hartz, they present similar palæontological, stratigraphical, and petrographical characteristics. The chain acquired individuality towards the close of the Palæozoic epoch in consequence of the extensive crumpling of the Palæozoic sediments and their associated igneous rocks. The final relief of the intense stresses which produced this crumpling appears to have been afforded by the intrusion of granite at many points along the chain. The basic igneous rocks, associated with the Devonian and Pre-Devonian sediments, are partly intrusive and partly contemporaneous (lavas and tuffs). They present essentially the same characters wherever they occur. The rocks of the Hartz and the Fichtelgebirge are often undistinguishable, either in respect of their original or secondary characters, from those of Devon and Cornwall. For our present purpose it will be convenient to separate the basic igneous rocks of the Lizard district from those of the rest of Cornwall and Devon. The latter are associated with Devonian-Carboniferous and lower Palæozoic strata, and they have been metamorphosed in late Carboniferous or Post-Carboniferous times: the former are associated with serpen-

tine and various schists, and the period of their metamorphism has not, as yet, been determined.

We are principally indebted to Messrs. Allport,\* Phillips,† Rutley,‡ and Worth,§ for the information we possess as to the petrographical character of the "greenstones" associated with Palæozoic strata. The classification of these rocks is attended with considerable difficulty in consequence of variations in structure and composition in one and the same rock mass.

These greenstones admirably illustrate the impossibility of separating rocks into sharply defined groups. We can describe the rocks, but to give each specimen a name, which shall denote its character, is impossible.

The variations in structure are partly original and partly secondary. The most important secondary structural characters are those which depend on the development of foliation. The passage of a massive into a foliated rock has already been referred to. The variations in composition are also partly original and partly secondary. The most important secondary characters depend upon the development of chlorite or some form of hornblende at the expense of augite, of leucoxene, and ultimately of granular sphene, at the expense of the titaniferous iron ore, and of water-clear secondary felspar and other substances at the expense of the original felspar.

Lavas and tuffs occur in the neighbourhood of Plymouth and Tavistock, in Devon, and of St. Minver and other localities in East Cornwall. They are probably also represented in West Cornwall by many of the so-called hornblende-slates, but the metamorphism in this region has been so intense that it is not safe to speak very confidently on this point. The intrusive rocks belong to the dolerite family of Mr. Allport, and from our point of view these are the most interesting. They have been less affected by surface agencies than the more porous lavas and tuffs, but they have been profoundly modified in certain localities by regional and contact metamorphism. The least altered rocks occur in the eastern portion of the district. The most common type appears to be an ophitic dolerite (diabase), with skeleton crystals of ilmenite. A

\* 'Quart. Journ. Geol. Soc.,' Vol. xxxii, p. 407.

† *Ibid.*, Vol. xxxii, p. 155, and Vol. xxxiv, p. 471.

‡ "The Eruptive Rocks of Brent Tor," 'Survey Memoir,' also 'Quart. Journ. Geol. Soc.,' Vol. xlii, p. 392.

§ 'Trans. Plymouth Inst.' 1886.

certain amount of chlorite is usually present. Examples of this type occur at Yealmpton, Rock, Park House, near Dartington, Pollaphant, Catacleuse, near Padstow, south of Anstie's Cove, near Torquay, and at South Pretherwin. Another type, containing deep brown "basaltic" hornblende (original), and a rich brown biotite (not the pale brown biotite so frequently developed near the contact with granite), occurs at several localities in the Plymouth district.

Dolerites of the above type have been profoundly modified by the granitic intrusions. The augite gives place to uraltite and actinolite, the felspar breaks up into a mosaic or into an aggregate of irregular and often perfectly colourless grains; the ilmenite becomes replaced by leucoxene, and a pale brown mica is often developed in considerable quantity. Tourmaline, axinite, and garnets sometimes make their appearance.

Where the rocks have been affected by pressure-metamorphism only, somewhat similar mineralogical changes occur. The hornblende is, however, generally paler, and the contact minerals (the mica, tourmaline, garnet, and axinite) are not present. The most striking feature in these regions is, of course, the development of schistosity, in the manner described by Mr. Phillips. In the Land's End district the two kinds of metamorphism have been superposed, and the contact minerals occur in the foliated rocks. It must not, however, be supposed that the foliation was produced at the time of the intrusion of the granite. The relation of the granite veins (*e.g.*, those of Trewavas Head) to the sediments clearly proves that the latter were crumpled and cleaved before the veins were intruded.

In studying the metamorphosis of the dolerites, the ophitic structure, when present, is of the greatest use. It is often preserved after the entire replacement of the augite by fibrous hornblende. Gmbel's term, epidiorite, becomes very useful if we limit it to dolerites in which the augite has been entirely replaced by hornblende. When the change has been accomplished without the obliteration of the ophitic structure, the rock may be termed an ophitic epidiorite. Now, the passage of ophitic dolerites into ophitic epidiorites, and, finally, into foliated hornblendic rocks, may be observed at many points in West Cornwall, as for example, at St. Ives, near Penzance, and east of Marazion. The foliated rocks differ somewhat from the typical hornblende-schists.

Let us now turn to the Lizard district. This district is separated geologically from the rest of Cornwall by a line of disturbance running from Porthalla on the east to Polurrian on the west. We are not able at present to speak positively as to the age of the rocks occurring on the south side of this line, or as to the date of their metamorphism. In the eastern portion of the district, between Porthoustock and Landewednack, innumerable dykes of "greenstone" occur in the gabbro and serpentine. They appear, however, to be entirely absent from the hornblende-schist, a fact (if it be a fact) very difficult to explain, on the assumption that the dykes are of later date than the hornblende-schist.

In the south-western portion of the district, about the Lizard Head, there is a zone of intense mechanical metamorphism, and in this zone we find lenticles and bosses of "greenstone" associated with actinolitic and hornblendic schists, which owe their origin, in part at least, to the metamorphosis of the greenstone. The general strike of the foliation planes in this zone is about N.N.W. and S.S.E., but there is often a considerable amount of local confusion.

The dykes on the eastern coast have been described by Professor Bonney, and to his descriptions I have little to add. In 1877 he arrived at the conclusion that "they were once all dolerites or basalts, and that the hornblende which undoubtedly characterizes many of them is a secondary product, due to metamorphism of the original pyroxenic constituent."\* Subsequent research has merely tended to confirm this generalization, at any rate so far as the vast majority of the dykes are concerned.

Macroscopically the rocks are of a dark purplish or greenish colour, and finely crystalline. They frequently contain porphyritic crystals of plagioclase. There is, however, no sharp line between the granular and porphyritic rocks, and specimens of both types may be often obtained from one and the same dyke. When examined with the microscope the rocks may be classed as dolerites, proterobases (rocks in which the augite has been partially replaced by hornblende), and epidiorites (rocks in which the augite has been completely replaced by hornblende). In some instances foliation has been superinduced by the pressure metamorphism which has affected the district. In these cases the different varieties may be described as foliated proterobases, foliated epidiorites, and hornblende-schists.

\* 'Quart. Journ. Geol. Soc.,' Vol. xxxiii, p. 915.

At Coverack, and immediately to the north, between this village and Manacle Point, there occur dykes which have preserved their original characters to a remarkable extent. The least altered of these are ophitic olivine-dolerites. The augite is often quite unaltered. It is almost colourless, and occurs in fair-sized masses, penetrated in all directions by the lath-shaped plagioclase. In one case distinct indications of a micro-pegmatitic intergrowth of plagioclase and augite were observed in a slide which showed, as a rule, the normal ophitic structure. The olivine shows no trace of serpentinization. It is, however, grey in colour, in consequence of the presence of minute dust-like particles. With a magnifying power of 1,000 diameters some of the largest of these can be seen to be of a dark reddish-brown colour. In some cases the particles appear to be distributed uniformly through the mineral. In other cases they are aggregated in parallel bands. The olivines are also traversed by irregular cracks, along which magnetite has been formed. The lath-shaped plagioclase is colourless, brown, or turbid. These conditions merely represent different stages of alteration, and may be observed in one and the same individual. Turbid plagioclase forms only a very small portion of the entire mass. As a rule the mineral is as fresh as in any of the Tertiary dolerites. Irregular grains and crystals of magnetite are scattered through the slides, and they are very often associated with a brown, nearly uniaxial, biotite. One or two dykes have been observed in which biotite plays an important part (mica-dolerites or diabases); as a rule, however, it is quite unimportant. It is interesting to note that the iron ore does not occur in the form of large skeleton rhombohedra. In this respect and in the presence of the dusty olivines these rocks differ from the ophitic dolerites of Devon and East Cornwall. They appear, however, to be in every respect similar to the "Ottfjäll-Diabas" of Törnebohm.\* In the majority of cases the dykes in the eastern portion of the Lizard peninsula differ from the above in having the augite, and, probably, also the olivine, replaced by secondary hornblende. They are, in short, epidiorites.

The plagioclase may be either turbid or water-clear, and the hornblende may be uralitic, actinolitic, or compact. In a large number of cases the structure of the epidiorites is distinctly ophitic; the lath-shaped felspars retain their outlines and penetrate

\* 'Neues Jahrbuch,' 1887, p. 272.



irregular masses of uralitic hornblende, which correspond in form to the original ophitic augite. Iron ores occur in the epidiorites exactly in the same way as they do in dolerites. The secondary hornblende is generally pale green; pale-brown varieties may, however, be occasionally observed. That the epidiorite and dolerite dykes are of the same age is proved by the similarity in their mode of occurrence, and by the fact that transitions may occasionally be observed from one rock to the other in the same dyke. The uralitization or amphibolization of the augite appears to be accompanied by the development of hornblende at the expense of the olivine. In some of the dolerites the olivines may be seen to be surrounded by a narrow zone of a greenish mineral, which possesses the double-refraction of hornblende, and may probably be referred to this mineral.

Foliation has not been extensively developed in the dykes under consideration, but it occurs occasionally as we have already mentioned. It is often of the flaser-type, but we sometimes find the more even foliation characteristic of the hornblende-schists. Prof. Bonney calls attention to a remarkable instance of the latter. It is found in a dyke occurring at the southern angle of the small beach in Caerleon Cove, about a stone's throw from the Poltesco Serpentine Works. Thus he says:—"It is from four to five feet wide; the sides for about six or ten inches are very dark and compact, and so platy in structure as to be almost undistinguishable from some specimens of the hornblende schists. This structure is lost rather suddenly, and the rock assumes the ordinary aspect of an igneous rock, consisting of a finely crystalline mixture of white felspar and dark hornblende, with porphyritic crystals of the former as much as  $\frac{1}{4}$  inch long." Under the microscope the ground mass of the central portions of this dyke consist of pale green or brown hornblende, mostly fibrous (uralitic), felspar, either turbid or water-clear, and scattered grains of magnetite. The porphyritic felspars are turbid and have lost their individual action on polarized light. The rock from the margin of the dyke is principally composed of irregular grains of water-clear felspar, green hornblende, and magnetite. A little turbid felspar, giving lath-shaped sections, is present in some slides and absent in others. The micro-structure of the rock so far as it consists of water-clear felspar, compact hornblende, and magnetite is that of a crystalline schist; not that of an igneous rock. It

closely resembles that of the schist from the margin of the Scourie dyke.\* Apart from the direct evidence furnished by the field relations, the occurrence of turbid, lath-shaped feldspars would give a clue as to the origin of the metamorphosed rock.

The south-western portion of the Lizard district is, as we have already stated, a region of intense mechanical metamorphism. The structural characters of the rocks are similar in many respects to those which may be observed along the great line of disturbance in the north-west of Scotland. One type of rock very common in this highly metamorphic region is a green actinolitic or hornblende schist, and in association with this schist we find lenticles and bosses of epidiorite, often distinctly porphyritic and having the forms of the original porphyritic crystals (feldspars) well defined. These masses of rock, undoubtedly of igneous origin, never, so far as I know, take the form of dykes cutting through the schists, but are included in, and sometimes pass over by regular transition into, the schists of similar composition with which they are associated. The original relations of these masses of "greenstone" or epidiorite to the surrounding rocks have therefore been to a very great extent destroyed, and both the greenstones themselves and the surrounding rocks so completely metamorphosed that it is often impossible to determine their original characters in the present state of our knowledge.

The most easily recognizable igneous rock in this district is now a porphyritic epidiorite. Originally we suppose it to have been a porphyritic dolerite. The porphyritic crystals of feldspar are represented by white pseudomorphs, sometimes half-an-inch in length, the forms of the originals being perfectly preserved. These crystals are somewhat tabular in consequence of the conspicuous development of the brachypinacoid (010); the basal plane (001) and the prism faces (110 and  $\bar{1}\bar{1}0$ ) may also be recognized. In short, the crystals, or rather the pseudomorphs, have the forms characteristic of porphyritic dolerites. Under the microscope they are turbid, and rarely show any traces of individual action under polarized light. They lie in a dark green groundmass, which is resolved under the microscope into an aggregate of water-clear plagioclase, uraltic and actinolitic hornblende, and opaque iron ore.

\* I ought to have mentioned that the schist made out of the marginal portions of the Scourie dyke is finer in grain than that made out of the central portions.

The felspar of the groundmass usually shows more or less lath-shaped forms, but sometimes the mosaic structure may be observed. Quartz very probably occurs in association with this plagioclase, but has not been recognized with certainty. In addition to the porphyritic epidiorites above described, we find also non-porphyrific rocks of a similar character.

The lenticles and bosses of definitely recognizable igneous rocks vary in size. They may measure a few inches or a few feet in diameter. They lie, for the most part, perfectly isolated in green actinolitic, hornblendic, or chloritic schists. Sometimes the bounding surfaces are tolerably sharp; at other times the external surfaces of the igneous rock are schistose, and it is impossible to say where the massive rock ends and the schist begins. In studying the development of schistosity, the porphyritic epidiorites are of great interest, because the porphyritic crystals often remain as more or less rounded "eyes" in the actinolitic schist. We will now describe one of these "augen-schists." Examined macroscopically the rock is a green satiny schist, containing small white spots which sometimes show the outlines of felspar, but are, as a rule, more or less lenticular in form. In thin section the groundmass of the rock is seen to consist of long actinolitic needles, water-clear grains of felspar, and grains of leucoxene. The needles are arranged approximately parallel to each other in the plane of schistosity (direction of stretching). Where the streams of needles encounter the white spots (turbid felspar pseudomorphs) they sweep round them in the graceful curves characteristic of fluxion structure. The water-clear substance is certainly in many cases biaxial, and, therefore, may with considerable confidence be referred to felspar. It may be said, in a certain sense, to play the rôle of groundmass, for actinolite needles often lie embedded in it. Grains of a nearly opaque substance, in part brown granular sphene, evidently represent the iron ores of the original rock. The "eyes" in the schist are turbid felspar pseudomorphs, similar to those which occur in the porphyritic epidiorites. Their angles have, however, been mostly rounded off. The rocks above referred to are best studied in the neighbourhood of Polpeor, and between that point and Lizard Head.

One conclusion of general interest may be drawn from a study of the metamorphic phenomena of the south-western portion of the Lizard district. We have seen that a clue to the origin of many

of the green schists is given by the "eyes" or lenticles which these schists contain. According to the view we have adopted, these "eyes" are portions of the original rock which, for some unknown reason, have escaped metamorphism. Now, if this be correct, it will be found to be of widespread application. "Eyes," or lenticles, of all sizes, ranging from microscopic dimensions to areas occupying many square miles on a geological map, are often found in regions of crystalline schist. It is to these "eyes," or lenticles, and to their relations to the surrounding rocks, that we must look for a solution of many of the problems relating to the origin of the schists.

So far we have been referring only to rocks of the dolerite group. The phenomena of pressure metamorphism are equally well illustrated in rocks belonging to the gabbro group. In his classic work on the origin of the crystalline schists; Dr. Lehmann maintains that the passage of gabbro into hornblende schist in the granulitic region of Saxony is the result of the deformation of masses of gabbro by powerful mechanical stresses. Dr. Hatch\* has applied the same theory to account for the phenomena observed in certain rocks from the valley of the Wildshönan. I have ventured to apply the theory to the gabbros of the Lizard. In this district we find every transition from massive gabbro to a typical crystalline schist. The change in structure is always accompanied by a change in the mineralogical composition of the rock. The original rock is essentially composed of labradorite or bytownite and augite or diallage. Olivine occurs in certain varieties. With the development of foliation the original ferro-magnesian minerals disappear, and their place is taken by hornblende; the felspar at the same time passes over into a dense white aggregate—the so-called saussurite. The different varieties of foliated rocks may be designated flaser-gabbro, augen-gabbro, and gabbro-schist. The gabbro-schist is sometimes undistinguishable from certain varieties of the hornblende-schist of the district, but I prefer to call it gabbro-schist, because in the present position of our knowledge we should not be justified in concluding that all the hornblende-schist of the district, or even any considerable part of it, has been made out of gabbro.

In reviewing the whole subject we are naturally led to ask—What light do the facts throw on the origin of extensive masses

\* 'Tschermak's Mitth.,' Vol. vii. (1885), p. 75.

of crystalline schist? Must we regard all hornblende-schists as the result of regional-metamorphism, operating upon basic igneous rocks? So far as these questions are concerned I will confess at once that I have not made up my mind. I am quite unable to recognize any characters by which we can separate the schists, undoubtedly formed by the metamorphosis of basic igneous rocks, from many of those whose origin is unexplained. If, therefore, we were justified in assuming that all basic hornblende-schists had been formed in the same manner, there would be no doubt in my mind as to the way in which the question should be answered so far as these are concerned. In studying the Lizard schists I have been much struck by their frequent resemblance to metamorphosed gabbros and dolerites, by the general absence over the areas occupied by hornblende-schist of intrusive masses of gabbro and greenstone, and by the occurrence in certain localities, especially near Mullion Cove, of "eyes" or lenticles of coarser grain and less marked foliation than the main mass of the schist. These "eyes" bear the most striking resemblance, both macroscopically and microscopically, to some of the highly metamorphosed gabbros. In no single instance have I ever seen either gabbro or greenstone undoubtedly intrusive in the hornblende-schists of this district.