33. *The ORIGIN of the CRYSTALLINE SCHISTS of the MALVERN HILLS.*

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[Abridged.]

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I. INTRODUCTION.

THE crystalline rocks of Malvern are of exceptional importance to the student of the problems of metamorphism, inasmuch as the causes in operation have acted with comparative feebleness, and thus have not obliterated the earlier stages of their work. Hence we are able in numerous sections to observe the details of the process by which a massive igneous rock has been converted into a well-foliated schist.

In my first paper¹ on the subject, I gave an outline of the mode in which some of the schists had been formed. In the second,² I described the most important mineral changes that occur at the zones of shearing. It now remains to work out certain structural details, to meet difficulties arising or suggested in the course of the enquiry, and to classify the chief varieties of schist in the light of their mode of origin. I would add that five years' study of these rocks has enlarged my belief in the efficacy of dynamo-metamorphism, to a degree which I should hardly have conceived possible when I presented my first paper to the Society in 1887.

In the present communication, it will be unnecessary to refer to minerals which do not play an essential part in the metamorphic process. Apatite, for example, does not, so far as the writer has observed, undergo any change. Sphene, garnet, and rutile are

¹ Quart. Journ. Geol. Soc. vol. xliii. (1887) p. 525.

² *Ibid.* vol. xlv. (1889) p. 475; these papers will (in the following pages) be referred to respectively as No. I. and No. II.

probably secondary products; but the first and second have been noticed in No. II., while the last occurs in very inconspicuous proportion.

Particulars of dips and strikes, and details of rock-distribution, will be found in Dr. Holl's memoir,¹ and descriptions of the principal rock-types in Mr. Rutley's paper.²

I have to express my great obligations to Messrs. J. H. Player and T. H. Waller for chemical analyses; also to Dr. G. H. Bailey and Dr. Cohen, of the Owens College, Manchester, for superintending several analyses.

II. CONFIRMATION FROM OTHER SOURCES OF SOME POINTS IN THE AUTHOR'S FORMER PAPERS.

Secondary Minerals produced during Dynamo-Metamorphism.—Prof. G. H. Williams, in describing the 'Greenstone-schist Areas of the Menominee and Marquette Regions of Michigan,' Bull. U.S. Geol. Surv. 1891, No. 62, states that the new minerals formed during the production of these schists are albite, microcline, zoisite, garnet, quartz, hornblende, epidote, biotite, muscovite, sericite, rutile, anatase, and sphene.

This list corresponds with that of the secondary minerals recognized by me in the Malvern schists (No. II.), except that the secondary plagioclastic felspar of my papers could not be specifically identified, owing to its minutely-granular structure; but as the rock containing it is sometimes almost destitute of lime, much of it may safely be referred to albite. Prof. Williams mentions anatase, which I have not recognized at Malvern, and, on the other hand, my list includes calcite, chlorite, and iron oxides, but these are of course very commonly produced in rock-crushing.

Production of Secondary Biotite.—The conversion of *Chlorite* into *Biotite* is recorded by Salomon, Zeitschr. d. Deutsch. geol. Gesellsch. vol. xlii. (1890) p. 450; also by Lossen, Congrès Géol. Internat. Londres 1888, Compte-Rendu, p. 180, and Rüdermann, Neues Jahrb. v. Beilage-Band (1887) p. 643.

The formation of *Biotite* out of *Chlorite* and *Sericite* is asserted by M. A. Michel-Lévy ('Sur l'Origine des Terrains cristallins primitifs,' p. 58, Congrès Géol. Internat. Londres, 1888).

The production of *Biotite* in *Shear-zones*, when none of that mineral occurs in the walls of the shear-zones, is recorded by Mr. J. F. Kemp in a paper on 'The Great Shear-zone near Avalanche Lake in the Adirondacks,' Amer. Journ. Sci. vol. xlv. (1892) p. 109.

Production of Muscovite from Biotite.—This change has been actually effected in the laboratory by Mr. Alex. Johnstone ('Nature,' vol. xvi. Sept. 29th, 1892, p. 518). Mr. Johnstone states that "by the continued action of carbonic acid, oxygen, and water, biotite loses magnesia (taken out as carbonate), and iron (removed either as oxide or carbonate), and becomes eventually the

¹ Quart. Journ. Geol. Soc. vol. xxi. (1865) p. 72.

² *Ibid.* vol. xliii. (1887) p. 481.

white and yellow muscovite which undergoes no further chemical change." Hornblende, according to the same authority, loses only a trace of magnesia under similar circumstances; but since hornblende is easily decomposed into chlorite, and chlorite may be changed into biotite, it is plain that hornblende may indirectly be a source of muscovite.

III. STAGES OF METAMORPHISM.

(1) *Decomposition and Corrosion*.—Ordinary decomposition, such as the passage of hornblende into chlorite, epidote, and iron oxide, or the conversion of plagioclase into calcite and quartz, appears to be associated with the access of mineral solutions. Where the rigid rock is crushed, there is always more or less decomposition, and the presence of water is evinced by the nature of the deposits which fill the cracks. Generally speaking, the crushing accelerates the process. When the pressure has increased so as to produce planes of discontinuity, decomposition is greatest at these planes. Thus, in a diorite the planes of cleavage or shearing are often marked by secondary products, while the intervening seams are comparatively unchanged.

Corrosion requires special mention. Crystals of hornblende, felspar, and some other minerals are very commonly corroded in an excessive degree in and near granite-diorite complexes. Idiomorphic individuals thus appear perforated with holes, or their margins are cut like a dentate or crenate leaf, and frequently the original crystalline form is nearly or entirely destroyed. The change is most common in the medium-black diorite.

The hornblende of this diorite sometimes shows curvilinear outlines at considerable distances from a sheared plexus of veins, and I must not be understood to deny that in these cases the mineral may have originally crystallized in this form; but the characters become more marked towards the zone of shearing, the crystals being more and more deeply eroded until only shreds of them are left. The mineral which remains in contact with the eroded part is generally transparent and water-clear. It is sometimes quartz, sometimes felspar. The latter occasionally displays polysynthetic twinning, but usually it is recognized as felspar only in convergent light. Hornblende can rarely be followed into a granite-diorite shear-zone, since it is normally converted through chlorite into black mica. This mica also frequently suffers corrosion, is reduced to shreds, and sometimes destroyed.

The corrosion of the felspar is very similar. The crystals are invaded by quartz or water-clear felspar, and sometimes the original substance entirely disappears. Frequently, simple felspar-crystals sheathed in biotite are replaced by quartz, the mica remaining intact. More commonly, the corrosion has acted in patches, so that a large part of a slide of modified diorite may be occupied with water-clear granules. Corrosion in felspar and biotite is shown in fig. 3 of pl. xvi, in paper No. II.

The rounded or lobate forms of crystalline grains have long been recognized¹ as characteristic of gneiss, as distinguished from granite.

Corrosion during the primary consolidation of granite has been fully described by Prof. Sollas, who states² that muscovite corrodes biotite, albite corrodes biotite, orthoclase and quartz corrode albite.

(2) *Reconstruction*.—In the course of my present enquiry, I have often been met by a demand for signs of mechanical force, such as broken or distorted crystals, shear-planes, decomposition-products, or strain-shadows. These, however, are the effects of an early stage of the metamorphism, and it would be as reasonable to expect them in the completed product as to look for petals and stamens in a strawberry.

Fortunately, at Malvern mechanical force has acted so intermittently that the stages of metamorphism can be followed from beginning to end in scores of sections. For example, the change from felsite or diorite into mica-gneiss can be traced inch by inch, the mineral decompositions and syntheses can be verified step by step, and we are thus forced to unite the extremes by countless intermediate links, and to conclude that the schist has been formed out of the massive rock.

The process of reconstruction often commences almost as soon as the decomposition. Take the case of a granite-diorite shear-zone. While the hornblende of the diorite may be passing into a chlorite, some of the felspar may be replaced by quartz and muscovite, and these are ultimate products. When, within the shear-zone, the chlorite has passed into black mica, more of the quartz and muscovite will have been generated. Iron oxide, liberated in an early stage, is either absorbed later on, as in the change from chlorite to biotite, or it aggregates into definite crystalline forms. The acidic constituents, quartz and felspar, fill up the spaces between the micas and any other basic mineral which may remain. The rottenness and dirty appearance produced by the presence of chlorite and disseminated iron oxide disappear, and a sound clear gneiss results.

The gneissic rocks have undergone but little mechanical change since the secondary consolidation, and their minerals, even the biotite not excepted, rarely show undulose extinction.

IV. CLASSIFICATION OF THE MALVERN SCHISTS.

In paper No. I. the present writer divided the Malvern schists and gneisses into two groups, viz. :—*Simple Schists*, or those formed from one kind of rock, and *Injection-Schists*, or those produced by the interveining of two varieties. The subsequent discovery of the infiltration-gneiss of the Wych makes it necessary to subdivide the latter group into (a) Schists of Primary Injection and (b) Schists of Secondary Injection.

¹ T. G. Bonney, Pres. Address, Quart. Journ. Geol. Soc. vol. xlii. (1886) *Proc.* p. 92.

² 'Contributions to a Knowledge of the Granites of Leinster,' Trans. Roy. Irish Acad. vol. xxix. (1891) p. 492, *et alibi*.

(A) SIMPLE SCHISTS.

The following are the most important varieties :—

Hornblende-gneiss (from *Diorite*). This schist involves the minimum of metamorphism. The constituents have been re-arranged, and quartz has been generated. The change is too well-known to need description.

Biotite-hornblende Gneiss (from *Diorite*).—Between bands of the gneiss just named and the biotite-gneiss which often forms the core of a veined plexus, the rock becomes progressively compressed, and biotite begins to appear. A slide (391)¹ offers the following characters :—

The hornblende has lost its clearness and cleavage, is irregularly stained with iron oxide, and is drawn out in the direction of schistosity into irregular ribbons or even strings. Sometimes, however, it retains perforations and traces of sinuate contours.

The felspar is not so clear, but is here and there clouded by partial decomposition. Quartz invades it in aggregates with mosaic polarization. Quartz also, or a water-clear mineral like quartz, usually occupies the perforations in the hornblende, whether within the crystal or at the margin.

The biotite is well characterized. It is strongly pleochroic, changing from light-brown to nearly black. The laminae lie parallel to the general schistosity of the rock. A little chlorite is associated with this mica. The felspar and quartz are perfectly moulded upon both biotite and chlorite, as well as upon the distorted hornblende: a flake of mica, or chlorite banded with mica, having sometimes one extremity in the middle of a felspar-crystal, and the other end in the middle of another crystal.

The slide is traversed by a large number (from 12 to 20) of cracks (shear-planes?) running roughly with the foliation. They cut through crystals of felspar and granules of quartz, and are clearly connected with the distortion of the hornblende, for the latter suffers unusual elongation where they pass through it, and it is often drawn out at the end into a long tail occupying a crack. The formation of the biotite is also dependent upon the cracks. A large proportion of it is seen to lie either in a crack, or in the line which a crack would take if produced. Or a mica-flake tails out in an attenuated film of brown matter, which is continued along a crack. I cannot resist the conclusion that this mica has been formed by the action upon the decomposed hornblende of mineral solutions infiltrated into the planes of discontinuity.

But we are met with an apparent difficulty. The felspar and quartz must have been in a plastic state subsequent to the distortion of the hornblende and the genesis of the mica, for the former two are moulded upon the latter two minerals. How is it then that the cracks still remain? The answer is (1) that to a large extent they have been obliterated: none of them can be traced all the way

¹ These numbers indicate throughout the numbers of the slides in my own collection.

across the microscopic section. And (2) that we can observe under a high power that the thinnest visible cracks are occupied by brown matter (iron oxide?) in minute particles. This film has apparently been sufficient to prevent the coalescence of the sides of the crack when plasticity supervened.

If the biotite be regarded as an original constituent of the rock, the planes of discontinuity must have been formed after it; and, as the cracks and flakes often coincide, the mica must frequently have been torn and distorted. But such is not the case. While the hornblende is more or less decomposed and deformed, the biotite in the cracks is idiomorphic and clear, frequently showing in section lath-shaped forms, rectangular or oblique, with the ordinary parallel cleavage.

The difference between this schist and the hornblende-gneiss gives us a hint of the important part in metamorphism played by mineral solutions infiltrated along cleavage-planes and cracks. The absence of cracks in the hornblende-gneiss probably accounts for the slight degree of mineral change. Water was of course present, for chlorite has been produced. But the rock which was converted into biotite-gneiss, traversed as it was with countless cleavage-planes, must have been saturated like a sponge. This principle is of wide application.

Muscovite-chlorite Gneiss (from *Diorite*).—This schist is not of wide distribution at Malvern. I showed in No. II. (p. 480) that in or near a granite-diorite complex, muscovite was sometimes formed from the felspar of the diorite, and not biotite from the chlorite.

Sericite-gneiss and *Muscovite-gneiss* (from *Diorite*).—The transition which will now be described is one of the most interesting that I have studied. At one end of the series we have a granitoid diorite; at the other, a fine-grained schist of acidic composition. The typical sections have been repeatedly visited during three years, and 39 slices of the rock have been examined.

The schist occupies the western side of the long spur running from the summit of Ragged Stone Hill in a southerly direction to the village of White-leaved Oak. The band is several yards broad, but possibly extends farther westward under the Hollybush Sandstone. Towards the eastern slope of the spur, the schistose structure becomes fainter, and the rock resembles a roughly laminated grit. In the quarry at the village, this gritty material graduates into the diorite. The complete transformation is seen in section in this quarry. The description will be taken from east to west, that is, from the diorite through the grit into the schist, a distance of about 50 yards. The structural planes, whether in schist or grit, dip at a high angle to the north of east.

We work along the northern side of the quarry, commencing where an irregular buttress is thrust forward, the rock to the east being decomposed and of no interest in the present investigation. The projecting mass is about two yards wide; in the middle of it is the diorite, a vein of granite runs up the eastern side, and several

veins of felsite appear in the western surface. In the lower face of the rock the diorite is quite recognizable as the coarse-grey variety (No. 3), but is rather crushed and decomposed. Following this rock up the slope, we see that the crushing and rottenness increase, while aggregation of the constituents becomes very marked. Thus, one hand-specimen is nearly all crushed felspar, with perhaps some infiltrated calcite and chlorite; another is mostly chlorite; in a third, iron oxide predominates. Near the top of the slope, a little to the left of the buttress, a rough schistosity sets in. Felspar in small irregular fragments, sometimes in recognizable portions of the crystals, lies in narrow parallel seams. The groundmass is chlorite, passing into brown mica, with a great quantity of opaque dust, presumably iron oxide. The rock is curiously suggestive of a true sedimentary grit. Much of it is very rotten, and specimens for the microscope are hard to get.

For several yards to the west there is little change. Then the outcrop is interrupted by soil and débris, but the exposures show that the rock is becoming more and more comminuted. Masses of felsite appear here and there up to the end of the section, but no more granite is seen, though there is plenty on the southern side of the quarry. Just before the Hollybush Sandstone is reached, marked reconstruction sets in. The rock becomes clearer and sounder, and the schistosity more strongly marked. The last series of changes is best observed by leaving the quarry and ascending the spur: the gradation from grit to schist is seen at many points on the ridge. Veins of granite sometimes appear in the schist, and are sheared out into bands of thinly foliated, contorted gneiss. A little south of the western summit, granite also veins the grit, but is not schistose. Just at the western summit, the passage from grit to schist may be seen in the same hand-specimen, and even in the same slide. A series of micro-slides in my collection illustrates the above general description.

There is so much crushing and decomposition in the rocks of this locality that I have been unable to obtain a specimen of the diorite that is unaltered. There is no doubt, however, that it is a modified form of the rock which Mr. Rutley has described¹ as a 'hornblende-gabbro.'

Slides Nos. 454, 455, and 456 (fig. 1).—These specimens are taken from the lower part of the projecting wall, and differ very slightly from each other and from Mr. Rutley's type. The hornblende shows very clearly the prismatic cleavages, but is much crushed and distorted. Here and there it has been changed into chlorite, especially along the cleavages. The chlorite is pale green in ordinary light, shows slight pleochroism, and under crossed nicols is nearly black with slight mottlings of grey. Epidote is abundant: it is usually in dirty aggregates without regular boundaries to the individual granules. There is a little white mica in minute flakes: it is clearly secondary, being moulded on the contours of the epidote and the jagged projections of the broken hornblende-prisms.

¹ Quart. Journ. Geol. Soc. vol. xliii. (1887) p. 493.

Quartz is in very minute proportion. Calcite is abundant, either in crystalline aggregates enclosed in other minerals, or forming venules, which sometimes occupy long irregular cracks, that also contain opaque matter and occasionally epidote. There can be little, if any, dolomite in the rock, for it effervesces freely with acids, and under the microscope we can often recognize the polysynthetic twinning parallel to faces of the rhombohedron $\frac{1}{2}R$, so characteristic of calcite.

Fig. 1 (Slide 456).

Diorite No. 3. The hornblende crushed and distorted, and the feldspar moulded upon it. The hornblende is partly decomposed into chlorite, epidote, calcite, and iron oxide. Unshaded portions are spaces where the rock has been torn away in grinding.

The feldspar requires special notice. It is certainly secondary, for it is moulded to the jagged and frayed edges of crushed hornblende-crystals, and encloses shreds of that mineral. It is also moulded to and sometimes encloses chlorite and opaque black matter, presumably iron oxide, both of which have been derived by decomposition from the hornblende. The species of this feldspar cannot be determined. It is slightly decomposed, preserving in ordinary light a somewhat dingy appearance. Here and there, traces of multiple striping are faintly visible; but many of the forms, though clear enough to show twinning, if it were present, display a uniform colour under crossed nicols.

No. 466.—This slide is from the rock a few feet above that from which the last set were taken. There is a slight approach towards a parallel arrangement of the constituents. All the hornblende has disappeared. Calcite, epidote, and fragments of feldspar are scattered in a groundmass of chlorite, and the slide is very

much obscured by opaque matter in the form of disseminated dust, which must be iron oxide liberated from the hornblende. The chlorite, which is in irregular strings and patches, is in part similar to the last; but some of it is more strongly pleochroic (sap-green to pale yellow-green), and shows higher interference-colours. Here and there the green shades into brown, and the interference-colours rise still higher, so that there is apparently a passage into black mica. Under crossed nicols, most of the chlorite presents a confused appearance of aggregate polarization; but this is seen to be due to the presence of calcite scattered through the chlorite in numerous minute forms. The epidote requires no special notice.

Much of the felspar is in large crystalline forms, which are more or less cracked and broken, the fragments being sometimes drawn away from each other. The cracks are filled in with chlorite, calcite, and the opaque dust. This felspar is clearer than the last. Only a small proportion of it shows twinning of any kind. The bulk of the felspar polarizes in a rather irregular manner, some of the fragments showing several patches of different shades of colour with vaguely sinuate margins, suggesting an approach towards a mosaic structure.

This rock is traversed by cracks, roughly parallel to the schistosity, and more or less occupied with the products of decomposition. There has been considerable strain in the mass subsequent to the secondary consolidation, both felspar and calcite displaying undulating extinction during rotation of the microscope-stage.

No. 470. Three or four yards farther up the slope.—The crushing is greater, and the parallelism of the constituents more marked. The chlorite passes more frequently into biotite. The slide is traversed by several cracks filled with opaque brownish matter (limonite?), and where these cracks pass through chlorite, they are margined by a narrow band of the mica, as if the mica had been formed out of the chlorite by the addition of constituents supplied in the cracks. The felspar is not so clear as in the last slide. In many of the fragments it passes into a water-clear mineral, with the double refraction and interference-figure of quartz.

No. 473 (fig. 2). About 3 yards farther west.—The ground-mass of the rock is chiefly opaque matter and the brownish mineral which replaces the chlorite. I have spoken of this mineral (under No. 466) as suggesting biotite. It has the precise habit of the chlorite, occurring in patches and strings; but, here and there, where the mineral is brownest, an approach to a fibrous structure is seen, and the absorption in these fibres is greatest when they are parallel to the principal section of the polarizer. Under crossed nicols, the extinction is parallel, and the interference-colours are high. In hand-specimens, the glimmer of mica cannot be detected; but as the mineral has not developed distinct lamellæ, with cleavage, and barely even a fibrous structure, we should hardly expect to find reflecting-surfaces. I therefore provisionally describe this mineral as biotite. Some chlorite is associated with it.

The fragments of felspar immersed in this groundmass are smaller than in the preceding slides. Some of them are seen to be parts of the same crystal; while others lie isolated in the matrix. These seams of fragments, being roughly parallel, give to the rock its sedimentary aspect. Both quartz and felspar are present. The

Fig. 2 (Slide 473).

Diorite No. 3. Decomposition further advanced; felspars crushed into minute fragments, which lie in irregular seams. The matrix of the fragments is chiefly brown mica, chlorite, epidote, and opacite.

latter is often water-clear, and polarizes in the patchy manner described under No. 466, but not exactly like a true mosaic. Many of the fragments do not give interference-figures, and the difficulty of distinguishing quartz from felspar becomes yet greater in the following slides, in which the fragments are still smaller and the felspar often polarizes as a true mosaic. In the remaining slides of this series, I shall therefore often refer to the water-clear mineral as 'quartz-felspar.'

A few yards farther west, the rock becomes sounder, and, under the microscope, it is clearer, the disseminated ferruginous matter aggregating in strings, granules, or definite crystalline forms. Reconstruction appears also among the other minerals. The next slide is taken as typical of the partially reconstructed rock.

No. 485. From the ridge north of the quarry.—Black mica does not appear in considerable quantity, the hornblende being represented in great part by chlorite. The latter is partly in irregular patches, as before; but associated with this form of the mineral are numerous, minute, pale-green granules, sometimes shaped like globulites, margarites, and longulites. Microliths of a pale-green

transparent mineral are also present. These granules and microliths may perhaps belong to the chlorite family. Many of them run in streams lying in the direction of the general schistosity.

Associated with the chlorite is a small proportion of white mica. It is either in microliths with lath-shaped sections, or in larger crystals more or less rounded, but sometimes with distinct basal cleavage and laminae projecting in a step-like manner. Elongation is sometimes parallel, sometimes perpendicular, to P. In both cases, the longer axes lie in the planes of schistosity, and accentuate the foliated structure.

The 'quartz-felspar' is very clear, and much of it has assumed a true mosaic structure. The granules of the mosaic, which are often very minute, have usually sinuate, occasionally foliate contours. The fragmental origin of some of the quartz-felspar is still evident; but on the whole there is a less clastic look about the slide, the angles of the fragments being often rounded off. Where they have been in contact, they have coalesced, and a broken stream of the minute microliths and granules of chlorite (?) marks the boundary between them, the quartz-felspar polarizing differently at the two sides of the line. Sometimes the minute chlorite (?) forms are enclosed in simple granules of quartz-felspar, where a union of fragments is unlikely. It seems therefore evident that the quartz-felspar has been more or less fused or dissolved, so as to permit not only of the coalescence of fragments, but of the inclusion of foreign minerals.

The last rock passes *gradatim* within 2 feet into a well-marked schist, showing in hand-specimens a clear foliation with glistening mica-surfaces. The next slide illustrates the minute structure.

No. 486 (fig. 3).—The slide is quite free from cloudiness, and the parallelism of the constituents is very marked. This is seen in several lines of minute opaque granules, which possibly indicate the position of shear-planes, as well as in the arrangement of the mica, chlorite, and quartz-felspar. The chlorite and the white mica are present in about equal proportions. They sometimes pass into each other by imperceptible gradations, the green colour of the chlorite shading into the transparency of the mica in ordinary light, as the dark shades of the interference-colours of the former graduate under crossed nicols into the bright hues of the latter. As I have already discussed the passage of chlorite into white mica (No. II., p. 488), I need not here repeat the details of this important mineral change; but, as tending to confirm the evidence offered in these papers, I may quote Prof. Judd's¹ observation of a *gradual* transition from basic lime-felspar towards an acid alkali-felspar, the optical characters changing *pari passu* with the diminution of lime.

That the white mica was either formed from the chlorite or generated contemporaneously, is evident from the fact that, in this slide (as in many others), the two minerals are frequently associated

¹ Quart. Journ. Geol. Soc. vol. xlv. (1889) p. 180.

in the same crystalline form, the chlorite being regularly intergrown in repeated laminæ parallel to the basal plane of the mica. Some of the mica occurs in irregular patches elongated in the direction of the schistosity, and it is this kind which graduates into the chlorite. Sometimes the mica is in such minute microliths, and is so intimately mixed up with the granules of quartz-felspar, that a graphic representation of the facts is impossible.

Fig. 3 (Slide 486).

Intermediate between the diorite and the schist. The lightly-shaded parts are 'quartz-felspar' and white mica; the darker patches are brown mica and chlorite. Some of the chlorite is intergrown with the white mica. A fracture in the rock passes across the slide. Some traces of shear-planes are accentuated by opaque matter.

The changes seen in the quartz-felspar are very instructive. The outlines have become more rounded, and there is a general elongation in the direction of foliation, so that fusiform shapes are common. The mosaic structure is more frequent, and none but the smallest particles polarize as a unity. In the secondary consolidation, the mica and chlorite are the first formed, and the quartz-felspar is moulded upon their contours.

The rock here described is a true crystalline schist, as seen in the parallelism of the minerals, the absence of clastic structure, the granulation of the quartz-felspar, and the crystalline condition of all the constituents.

Here and there in the band of the schist, specimens (No. 347, fig. 4, p. 411) may be obtained in which the metamorphism has proceeded still farther. The chlorite has almost disappeared, and the rock mainly consists of lenticular or linear mosaics of quartz-felspar enclosed in a meshwork of fibrous white mica, which

apparently belongs to the sericite family. The quartz-felspar contains few, if any, cavities. It is largely penetrated by microliths of the mica, which often forms an interrupted sheath to individual granules, representing, it may be, the original fragments. The process of reconstruction is most marked in the ferruginous matter. Besides opaque granules, there are several linear aggregations of iron oxide in regular forms, many of which are seen by their cubic crystallization to be magnetite.

Some confirmatory proof of the secondary origin of the white mica will here be added. The calcite liberated during the decomposition of the diorite often appears in considerable quantities in the schist. It is in single granules, definite forms, or venules. When the venules cross the foliation, they are often shifted in the direction of foliation at the junction of the quartzose folia with the mica-folia. Here and there the continuity of a vein is broken by a flake or bundle of white mica, but is renewed along the same line at the other side of the flake. It would therefore seem that some part of the schist-making process, and the production of some at least of the mica, took place after the liberation of the calcite. In slide 428 the evidence of the secondary origin of the mica is of a different kind. A venule of calcite runs with the foliation, at first tapering almost to a line, then swelling out into a thick lenticle. On each side, the venule is sheathed in bundles of white mica, whose laminae follow precisely the contours of the enclosed calcite, bending inwards at the narrow neck, and curving outwards to enclose the lenticular head. The curvature of the mica is rendered more distinct by a number of enclosed scales of iron oxide (seen in section), which lie in the general direction of the cleavage, and thus appear to flow round the contours of the calcite. In the same slide is seen another lenticle of calcite wrapped round by a sheath of mica. The mica, being thus moulded to the calcite, must be of contemporaneous or posterior origin.

Another series of slides, taken from the summit of the hill, points to a somewhat different process of schist-making from that just described. The chlorite is first converted into biotite, and this passes into a fibrous or scaly white mica. These changes are described in No. II. (p. 488). The felspar is sometimes replaced by a highly-refracting mineral with low interference-colours, and occasionally a columnar structure: it may be zoisite. This mineral does not, however, appear in the completed schist, in which the felspar is represented by the usual mosaic.

A slide (303) from this locality shows a very interesting passage between the grit and the schist. The field is mostly occupied by fragments of felspar, the highly-refracting mineral, and water-clear mosaic, immersed in a groundmass of chlorite, passing into biotite with a distinctly lamellar structure. The whole has a schistose appearance, which is accentuated by numerous subparallel cracks, more or less marked by the presence of biotite and iron oxide. Towards one margin the schistosity becomes more pronounced. Spindle-shaped mosaics set in; and the chlorite and

biotite pass into flakes of white mica, whose cleavage-lines are often indicated by brown iron oxide. The gradation between grit and schist seen in this slide is unmistakable.

The explanation that I have given of the genesis of this schist may throw light upon certain cases in which authors have asserted an epiclastic structure in schists. It is obviously needful in such cases either to trace the origin of the fragments, or to establish reliable tests for distinguishing between epiclastic and cataclastic¹ structures.

Fig. 4 (Slide 347).

The sericite-gneiss. Near the centre of the figure is a little of the fragmental 'quartz-felspar' still remaining.

In summarizing the series of changes by which diorite is converted into sericite-gneiss, we observe that hornblende passes into chlorite, epidote, calcite, and iron oxide, where the crushing is only moderate. In the more highly-sheared rock, epidote is scarce or wanting. The most important part in the metamorphosis is taken by the chlorite: by a process of reconstruction it becomes either biotite or white mica, and the biotite also changes to white mica in the ultimate stage. The white mica is either in twinned crystals (muscovite) or in undulating bundles (sericite?). The felspar is first crushed into fragments, which are broken up smaller and smaller. Some of it passes into quartz; or a mosaic structure, in which it is often impossible to distinguish between quartz and felspar, is gradually produced. The fragments are then softened, and

¹ Terms proposed by Mr. J. J. H. Teall, F.R.S. (Geol. Mag. for 1887, p. 493). 'Epiclastic,' formed upon the earth's surface; 'cataclastic,' produced during deformation.

become agglutinated where they are in contact. The pressure produces elongation of the fragments and aggregations, which thus assume a linear or spindle-like form. The iron oxide, liberated as dust, passes through the form of granules of various sizes and shapes into regular crystals of magnetite, and sometimes perhaps hæmatite.

It is common in these rocks for contortion to set in when the schistosity becomes very marked and the mica abundant. The development of mica and the contortion of the folia appear to proceed concurrently.

Biotite-gneiss and *Biotite-granite* (from *Diorite*).—These rocks are formed from the diorite which yields the sericite-gneiss just described. The pressure has been comparatively slight, and the resulting changes are proportionately small. There is no sharp line of demarcation between the gneiss and the granite, the former being merely a more strongly-compressed form of the other.

There can be no question that this rock, whether gneissic or granitoid, has been formed from the diorite. Gradations between the two are numberless. They are best seen at the northern end of the range, especially in the North Hill and on the southern and eastern slopes of the Worcestershire Beacon, where there are many granitic intrusions, but only moderate pressures. At many spots the passage from a hornblendic to a micaceous rock is clearly seen to be connected with the intrusion of granite-veins.

Muscovite-gneiss (from *Granite*).—Described in No. I., p. 528.

(B) INJECTION-SCHISTS.

In No. I. (p. 532) I stated that at Malvern a banded gneiss was produced by the compression of masses of veined igneous rocks, duplex diorite-gneiss being formed from diorite veined by diorite, and granite-diorite gneiss from diorite veined by granite. This explanation received some support from Mr. J. J. H. Teall, who has since applied a similar interpretation¹ to certain banded gneisses at the Lizard. The cases which I then cited are comparatively simple, since the rocks described had undergone little chemical change; but it will be necessary in the present communication to add certain varieties of gneiss which are formed in the same way, but in which the transformation has been carried much farther. The gneisses in which infiltration has played a prominent part will come under the same head. The intrusion of rock in the original veining-process may be called *primary injection*, while we may describe as *secondary injection* the infiltration of mineral matter into rock crushed after consolidation.

The production of gneisses by primary injection has been noticed, among others, by Dr. Ch. Barrois,² but in the cases described by him the intrusion of the rock was into sedimentary strata. The changes thus caused differ in degree from those described in this

¹ Geol. Mag. for 1887, p. 484.

² 'Granulites du Morbihan,' Ann. Soc. Géol. Nord, vol. xv. (1887) p. 1.

paper, partly because the minerals composing a stratified rock are usually more stable than the constituents of diorite.

The evidence for the exotic origin of the granite is given in No. II. (pp. 494-496). Prof. John Phillips, writing of these Malvern rocks, also regarded¹ the "posteriority of felspathic and granitic veins to the masses they traverse" as "quite certain."

(a) Schists of Primary Injection.

Duplex Diorite-gneiss.—This gneiss is of no great importance. It is (or was) well seen in the large quarries at North Malvern. The medium black diorite is interlaced by the coarse grey variety, and a moderate amount of compression has produced a rough parallelism of the veins.

Granite-diorite Gneiss (No. I., p. 533).—It is necessary for the production of this gneiss that the granite-veins should be comparatively few, and that there should be moderate pressure with little shearing. Countless gradations may be traced between a rock in which there is merely a rough parallelism of the veins and a typical gneiss with one or two micas, so that it is impossible to draw a sharp line between a granite-diorite gneiss and a true mica-gneiss.

Banded Biotite-gneiss.—This is a rock in which bands of quartz-felspar (the injected granite-veins) alternate with seams of mixed biotite, felspar, and quartz (the altered diorite). To produce a biotite-gneiss out of a decomposed diorite, the chlorite must be mainly converted into biotite, the disseminated iron oxide must be either crystallized or absorbed, and quartz must be liberated. All these changes are known to frequently occur at Malvern. The conversion of chlorite into biotite and the liberation of quartz from felspar are extremely common. The recrystallization of iron oxide is seen in the section at Ragged Stone Hill, already described, and has been observed by other workers. The re-absorption is frequently illustrated in the present series of papers.

The evidence for the conversion of diorite interlaced with granite-veins into a banded biotite-gneiss is of the most positive and direct kind. One of the best examples is seen in the quarry at the southern end of Swinyard's Hill. The section is given in No. II. (p. 482), and the chief mineral changes are there described.

I cannot too emphatically insist upon the completeness of the gradation between diorite and gneiss. As we approach the plexus of granite-veins, the hornblende changes to chlorite and the chlorite to biotite. The felspar becomes invaded by quartz, and gradually assumes the normal corroded appearance. The parallel structure grows more and more distinct, and near the veins aggregation sets in. Even before we reach the plexus we obtain at contact with granite-veins a partially gneissic structure, a sort of foliated kersantite, seams of which cannot be distinguished from some of the bands in the very core of the plexus.

It does not seem to be essential that the veins in a banded biotite-

¹ 'Geol. of Oxford and the Valley of the Thames,' 1871, p. 62.

gneiss should be granite, though this is usually the case at Malvern. In two or three localities south of the Worcestershire Beacon I have observed a banded gneiss in which the veins were (or rather had been) the coarse grey diorite. Yet the mica was produced abundantly, both in the diorite encasing the veins and in the diorite of the veins themselves. At one inch from the veins the encasing rock, a fine-grained diorite, was highly altered, and consisted of hornblende, white mica, epidote, chlorite, and quartz, but not much feldspar, the minerals being arranged with a rough foliation. Near the contact with the veins black mica was developed in fair proportion.

These apparent exceptions to the general principle admit of an easy explanation. In the large number of slides examined I have usually found biotite to be generated in diorite when the rock is sliced by planes of cleavage or shearing, or when traces at least of such planes can be detected. Of course, when the diorite has been transformed into gneiss, planes of discontinuity have largely disappeared; but I am here speaking of rock in which the dioritic structure is still apparent. Diorite is often sheared without the production of mica, especially in Midsummer Hill, in which there is very little granite; but the mass of the Worcestershire Beacon is extensively penetrated by dykes and veins of granite, and it is here that we find so much biotite generated in the diorite.

Gneiss with two Micas.—I described in No. II. (pp. 478–481) a gneiss in which the dark bands (modified diorite) contained both black and white mica, and the light bands (modified granite) white mica. The muscovite was formed from both the orthoclase of the granite and the feldspar of the diorite, the biotite being produced in the usual way from the hornblende of the latter.

In closing this account of the origin of the banded gneisses of Malvern, it will be well to summarize the explanations of the banded structure which have been made public.

1. The hypothesis of original sedimentation.
2. That banding is produced when inclusions (say of diorite in granite) are fused and drawn out into parallel strips under earth-pressures. Some of these gneisses are described by Dr. A. C. Lawson.¹ The writer has seen similar structures near the town of Galway, on the east side.
3. By injection of granite along the bedding-planes of sedimentary rocks. See Dr. Ch. Barrois's works, *passim*.
4. By movements in plutonic rocks when in a viscid state (Prof. Bonney and Lieut.-General M'Mahon, *Quart. Journ. Geol. Soc.* vol. xlvii. 1891, p. 464).
5. By the deformation of veined complexes of igneous rocks under pressure. (Mr. J. J. H. Teall, *Geol. Mag.* for 1887, and the Geological Survey, *Quart. Journ. Geol. Soc.* vol. xlv. 1888, p. 388.) Mr. Teall leaves the origin of the veins an open question; while the

¹ 'Report on the Geology of the Rainy Lake Region,' *Geol. & Nat. Hist. Surv. Canada*, 1887, p. 137.

Survey regard those observed by them in the Highlands as segregations and of contemporaneous origin.

6. The view expounded in the present series of papers. It approximates to the preceding explanation, but concludes that the veins are intrusive and posterior. How far this theory applies to regions outside Malvern the writer does not presume to suggest.

7. There are suggestions in the preceding pages and in No. II. that segregation during the shearing-process has sometimes produced a banded structure.

Gneissoid Quartzite.—There is not much to add to the explanation of the origin of this rock given in No. II. (pp. 485, 486). I there stated that it was an extreme phase of alteration in diorite. Since it is formed from the gneiss just described, I have included it under 'injection-schists,' although I by no means affirm that injection is necessary to its production. It is not very conspicuous at Malvern, occurring only (so far as I know) in a few narrow bands near the southern end of Swinyard's Hill. Sometimes it constitutes small patches and seams in the biotite-gneiss, and wherever I have seen it there is a gradation between it and the gneiss. In it the biotite has almost disappeared, muscovite is in equally small proportion, and we have little left but dull-looking felspar-crystals invaded by rounded granules of quartz or water-clear felspar, or entirely replaced by them. As there is little parallelism of structure, the rock approximates to a rather feldspathic quartzite. Indeed, it is very similar under the microscope to the rock which in Connemara has been usually described as a 'quartzite.'

This theory of the origin of the Swinyard's Hill quartzite receives important confirmation from a paper¹ by Mr. W. S. Bayley, of the Geological and Natural History Survey of Minnesota. Mr. Bayley concludes that a certain quartzite of the Animikie group, "though a completely crystallized quartzite, is nothing more nor less than an extreme phase of gabbro," or "a completely altered gabbro."

This rock will be again considered under Section VIII. of the present paper.

(b) Schists of Secondary Injection.

These are, I suspect, rather common at Malvern, but sections in which the process of infiltration can be demonstrated are rare. In No. II. (p. 496) I referred to a shear-zone at the Wych, in which a chlorite-gneiss was formed by the infiltration of chlorite (and iron oxide) from a decomposed diorite into the cracks and shear-planes of an adjacent mass of granite. The mineralogical changes were then briefly described, but the limits of the present paper preclude fuller details.

V. HOW FAR THE SCHISTS INDICATE THEIR ORIGIN.

Is it possible among the Malvern rocks to determine the origin of a schist from its structure and composition? The answer is usually

¹ Nineteenth Annual Report, Geol. & Nat. Hist. Surv. Minnesota, 1892.

'Yes'; but where the maximum of metamorphism has taken place, I should sometimes be obliged to reply in the negative. Take the sericite-schists of Ragged Stone Hill. Some of these schists are formed from diorite, some from felsite. Yet, under the microscope, both are sometimes seen to consist of apparently¹ the same materials arranged in a similar manner. The presence of a small proportion of iron oxide and epidote or chlorite does not help us, for those minerals are sometimes infiltrated into the shear-planes of the felsite. The schist produced from diorite is often more or less veined with calcite, which is not the case with the other variety; but slides of the former sometimes show hardly any calcite. However, even in the perfectly formed schist, there is often a residuum of the shearing-process in the form of a crystal or fragment of felspar, crushed, and tapering at each end in water-clear mosaic. This would seem to mark an origin from diorite, for the felsite of the locality never contains, so far as the writer has observed, a porphyritic crystal of felspar.

The case just selected is an extreme one, in so far as Malvern is concerned. I do not think there is any other schist in the district which, in a hand-specimen or a micro-slide, cannot be referred to its origin. A few of the chief types will be taken in illustration.

Banded Biotite-gneiss.—The granite-veins are, of course, easily recognizable. The micaceous seams also usually betray signs of their dioritic origin. There may be slides in which most of the felspar has been invaded by water-clear granules, and in which the mica is arranged in parallel seams; but a large proportion of the specimens examined contain patches of the kersantite-structure which have resisted the metamorphic forces. In these patches very little quartz has been generated, and the crystals of biotite are sprinkled among the felspars just as in the kersantite formed directly from diorite (No. II., pl. xvi. fig. 1).

Simple Biotite-gneiss.—The structure of the original diorite is fairly evident, the place of the hornblende amidst the felspar-crystals being taken by biotite, and the felspar being more or less invaded by quartz.

Muscovite-gneiss formed from Granite.—This variety often shows the 'eyes' of orthoclase so well seen in the *augen*-gneisses, described by Lehmann, Lapworth, Bonney, Teall, and others. Where these are absent, the rock may usually be differentiated from similar rocks which have been formed from diorite by the absence of plagioclase-felspar and of any trace of diorite-structure.

Chlorite-gneiss.—The remarks of the last paragraph will apply here, the infiltrated films of chlorite being interfoliated with the other minerals.

Gneissoid Quartzite.—I should have little hesitation in recognizing the derivation of this rock within the Malvern area. The marks of origin are the presence and arrangement of scraps of biotite, the

¹ Quartz and felspar being undistinguishable when in minute, water-clear granules.

occasional replacement of felspar by zoisite or epidote, and the frequent traces of kersantite-structure.

The traces of original structure in a rock of secondary origin may perhaps be appropriately described as 'residua.' The 'eyes' of an *augen*-gneiss or *augen*-gabbro, and the lenticular cores (lenticles) of granite in a muscovite-gneiss are the direct result of shearing. But the residua of kersantite in a biotite-gneiss are patches of rock which have escaped advanced molecular changes, and they are not as a rule sharply distinguished at their margins from the surrounding mass.

VI. THE NATURE OF THE SHEARING.

To remove some doubt that appears to exist with reference to my use of the terms 'shearing' and 'shear-plane,' I may state that I accept the definitions of those writers who in this country have been among the pioneers in these new studies.

Prof. Lapworth, describing¹ the process of schist-making in the Highlands, states that many of the rocks "have been crushed, mashed, and dragged out, their component patches, fragments, particles, and crystals *shearing* (or moving over each other with a differential motion, each higher layer moving a little farther than the one below) as the mass gave way." The same writer defines "shear-planes" as "definite planes" along which "the rock yielded to the excessive pressure and torsion" (*op. cit.* p. 114).

The Geological Survey, in their elaborate memoir on the Northern Highlands,² adopt a similar terminology. The lines of movement in the rocks are described as "thrust-planes, crush-lines, or lines of shearing, resulting in a newer foliation" (p. 391). In certain of the schists, each "shear-plane" is referred to (p. 435) as a "divisional plane or foliation-surface," and these planes are described a few lines before as the result of "powerful thrusts," producing "slices" in the rock.

The definitions and descriptions of Prof. Lapworth and the Geological Survey agree precisely with those employed in the present series of papers. They apply only to rock in the solid state.

VII. DISCUSSION OF THE QUESTION WHETHER THERE HAS BEEN A MIXING OF THE ORIGINAL MAGMAS.

The great variations of chemical composition seen in the Malvernian rocks have suggested to some correspondents a mixing of the acidic and basic magmas before consolidation. Perhaps the best reply to this suggestion is set forth by the facts contained in the present series of papers. There is evidence to prove an intermixture of chemical constituents, that, for example, potash has passed from granite to diorite, and soda from diorite to granite. But I have never been able to find that the magmas are mixed together, except perhaps

¹ 'Introductory Text-book of Geology,' 1888, p. 112.

² Quart. Journ. Geol. Soc. vol. xlv. (1888) p. 378.

occasionally on a small scale at their contacts. We have seen that the grey diorite was injected into the medium-black variety, that granite, felsite, and dolerite were subsequently intruded into the two preceding; yet each of these magmas is nearly always clearly and sharply distinguishable from the others.

The variations of chemical composition seen within the same rock-mass depend largely upon two causes—namely, the degree of mechanical energy, and the nature and quantity of infiltrated mineral matter. In numerous cases chemical change is seen to increase *pari passu* with the mechanical force, as in the conversion of diorite into sericite-gneiss at Ragged Stone Hill (pp. 404 *et seqq.*). The influence of infiltration is well illustrated at Swinyard's Hill (p. 413), where, as we trace the diorite into the granite-diorite complex, the percentage of potash in the diorite rises from 2·8 to 5·3.

VIII. THE CHEMICAL CHANGES.

The Elimination of Magnesia.—Most of the decompositions described in these papers are well known. The action of carbonic acid and alkaline carbonates, at the ordinary temperature and pressure, upon silicates of the heavy bases was described by Bischof. He held that in his experiments silicate of lime and protosilicate of iron were decomposed by carbonic acid in the wet way, but that silicate of magnesia was only slightly acted upon, and silicate of alumina not at all. He admits, however, that in nature silicate of magnesia is decomposed by carbonic acid, even at ordinary temperatures. Thus, he says that in springs carbonate of magnesia has been formed by the decomposition of magnesian silicates by carbonic acid. Again, in the conversion of olivine into serpentine magnesia is eliminated, and Bischof quotes a case said to occur at Snarum, where the serpentine thus produced is surrounded by bitter-spar. He also states that dolomite has been observed in limestone where it was in contact with basalt, the change being produced by the action of meteoric waters.

The researches of Mr. Alexander Johnstone, F.G.S., have an important bearing upon this enquiry. He concludes¹ that water containing carbonic acid exerts no chemical change upon *pure* mineral magnesian silicates; but that, even at the ordinary temperatures, carbonated water extracts magnesia from complex silicates, such as olivine. This mineral was exposed for two months to the action of distilled water saturated with carbon dioxide. The liquid was then found to contain magnesia, and the olivine had lost ·73 per cent. of that base. Mr. Johnstone exposed biotite-mica dust to carbonic-acid water for a year. He states² that, at the end of that time, the percentage of magnesia had been reduced from 20·04 to 17·35; and he suggests that an extension of the time of immersion would result in the further elimination of the base. From a long series of experiments, he concludes that

¹ Proc. Roy. Soc. Edin. vol. xv. (1888) p. 436.

² Quart. Journ. Geol. Soc. vol. xlv. (1889) p. 367.

"any ordinary hydro-biotite, such as voigtite, vermiculite, or pyrosclerite, exposed for a lengthened period to the action of carbonic-acid water, invariably lost a portion of its magnesia (and iron)." This investigation has been continued, and the results are summarized in Section II. of the present paper (p. 399). It is fair to assume that, at higher temperatures, to say nothing of pressures, the action of carbonated waters would be still more energetic.

The elimination of magnesia during the shearing-process seems to be absolutely demonstrated by the Malvern sections. No one who examines, for example, the section at the southern end of Ragged Stone Hill, and studies a series of the rocks under the microscope, can doubt that the sericite-gneiss was once a diorite. Yet the percentage of magnesia has fallen from 5 in the diorite to less than 1 in the schist. This is seen in the following analyses, the first four of which were very kindly determined for me by Mr. J. H. Player.

The specimens II., III., IV. are taken along the section from crushed diorite to schist. For comparison I append the composition of the same variety of diorite in an uncrushed state (I.) from another Malvern locality.

	I.	II.	III.	IV.
Silica	47·6	49·0	52·8	61·6
Alumina	17·6	19·0	15·8	18·6
Titanic oxide	1·6	1·2	2·6	·8
Ferric oxide	4·8	3·4	5·4	1·3
Ferrous oxide	5·8	7·5	9·5	5·1
Lime	8·6	2·8	·5	·2
Magnesia	5·0	5·3	4·1	2·6
Soda	2·3	2·0	1·3	1·6
Potash	4·3	2·5	1·9	3·7
Loss	2·2	6·5	5·7	3·7
	99·8	99·2	99·6	99·2

- I. A typical specimen of the coarse-grey diorite.
- II. The same variety crushed (taken near specimen No. 273), being a sort of grit composed of fragments of felspar in a groundmass of chlorite, biotite, and ferruginous dust.
- III. The grit just before it passes into schist. The rock has undergone partial reconstruction, the iron oxide has been recrystallized, and there is some free quartz. Sphene is in unusual proportion.
- IV. Sericite-gneiss, containing some chlorite. It is within one foot of No. III. in the same mass, and an intermediate specimen furnishes the slide (303) in which the actual gradation between grit and schist is seen. This analysis would give (roughly) the following percentages:—Chlorite = 10, white mica = 25, orthoclase (or microcline, or both) = 15, albite = 15, iron oxide = 5, quartz = 25, which corresponds very well with the appearance of the rock under the microscope.

It will be seen that in this series the silica rises in steps thus:—47·6, 49·0, 52·8, 61·6. Two analyses of other portions of No. IV., made for me at Owens College by the kindness of Dr. Cohen, give the silica percentages respectively as 64·96 and 73·13. The lime in the above series falls in steps thus:—8·6, 2·8, 0·5, 0·2. The magnesia also falls, but less rapidly, thus:—5·0, 5·3, 4·1, 2·6. No. IV. contains a fair quantity of chlorite; but Dr. Cohen's

analyses, which are from less chloritic specimens, yield respectively 1.29 and 0.35 per cent. of magnesia.

While lime and magnesia are gradually eliminated in the shearing-process, the alumina and alkalies are tolerably persistent. From this it follows that, in the extreme of metamorphism, there must be much free silica, and a part of the remainder will be in combination with a highly aluminous base. Hence the abundance of white mica.

Another series of analyses by Mr. Player furnishes similar results as regards the loss of magnesia. They illustrate the chemical changes undergone in the conversion of the medium-black diorite into a gneissoid quartzite.

	V.	VI.	VII.	VIII.
Silica	47.1	47.2	66.0	81.9
Alumina	18.1	17.8	16.6	9.2
Titanic oxide	.4	.4		Trace.
Ferric oxide	3.0	6.7	1.6	.6
Ferrous oxide	8.5	5.6	4.2	1.6
Manganic oxide	.1	...	...	...
Lime	6.6	4.8	.5	.9
Magnesia	7.3	6.3	1.9	.5
Soda	2.4	2.2	1.5	1.6
Potash	2.8	3.9	5.3	2.1
Loss	3.6	4.1	2.2	1.1
	99.9	99.0	99.8	99.5

V. Medium-black diorite, Swinyard's Hill.

VI. 'Basic rock' of Mr. Player. It is the same variety of diorite, but it has undergone some change, a parallel structure having been produced, and a little biotite has been generated. Malvern.

VII. Biotite-gneiss formed out of the same diorite at contact with granite-veins. Traced *gradatim* into V.

VIII. Gneissoid quartzite; a more advanced stage of VII. Swinyard's Hill.

It is probable that some, at least, of this magnesia has been removed as carbonate; but I have not been able to find dolomite or magnesite in the rock, and I desire to confine myself to facts actually observed or proved by experiment.

The Fall in the Percentage of Alumina.—The final stage in the conversion of diorite into an acidic gneissic rock is accompanied by a great diminution in the alumina. In the second series of analyses (V.–VIII.) it will be seen that this base falls to about one-half. As it may be contended that this reduction may be due to an original difference of magmas, a series of analyses has been very kindly made for me by Mr. T. H. Waller, B.Sc., from samples taken from the same block, which reveals under the microscope a perfect gradation between the biotite-gneiss and the gneissoid quartzite. One of the slides shows the sample X. (which is intermediate between biotite-gneiss and gneissoid quartzite, and displays very clear kersantite-structure) passing into the gneissoid quartzite (XI.), which differs chiefly in being much more quartzose, and still retains traces of kersantite-structure.

	IX.	X.	XI.
Silica	60.4	65.7	77.1
Alumina	18.6	17.2	10.9
Ferric oxide	3.5	.9	.7
Ferrous oxide	5.3	4.5	2.3
Lime	1.6	1.2	1.3
Magnesia	2.8	1.9	1.4
Soda	4.1	3.9	1.6
Potash	3.0	2.6	1.8
Loss	...	2.3	1.5
	99.3	100.2	98.6

IX. Biotite-gneiss. Swinyard's Hill.

X. Like IX, and from the same block.

XI. Gneissoid quartzite, passing gradually into X.

This fall in the percentage of alumina must arise either from its elimination, or from the introduction of silica. The microscopic evidence points towards the former alternative. In tracing the changes of the different minerals through a series of slides in which diorite and gneissoid quartzite are the two extremes, we observe, not the coming in of quartz between the other minerals, but the progressive destruction of these minerals themselves. The biotite produced out of the hornblende loses its idiomorphic form, and is reduced to shreds. The felspar is invaded by fingers and lobes of quartz, and is often entirely replaced by it, the sheath of mica which often surrounds felspar-crystals continuing to envelop the quartz-replacement. Of course, where the mica has nearly disappeared, and many of the felspars are deeply corroded or replaced by quartz, a considerable proportion of the alumina must have been removed. In some slides of the gneissoid quartzite there are a few crystals of garnet; but the bulk of the alumina cannot be accounted for in this way.

In the felspar of the granite-veins there is also corrosion and replacement by quartz, so that, especially in the small veins of shear-zones, the granite is converted into quartz. Alumina must have been removed in this case also.

What becomes of the eliminated alumina? I am not prepared to answer this question; but I have noted many facts at Malvern and elsewhere which seem to indicate that, during advanced dynamic deformation, there is set up a tendency towards mineral aggregation. In the Malvern district, the diorite which has undergone extreme alteration sometimes occurs as a schist, in which seams which are mainly mica alternate with seams which are almost pure quartz. The conclusion appears inevitable that alumina has migrated from one place to another, probably as silicate. However, I merely suggest this point, with a view to further enquiry.

Elimination of the Oxides of Iron.—A glance at the above analyses reveals a reduction of iron oxide in the process of schist-making. This fact may have some bearing on the origin of iron ores.

IX. SECONDARY CONSOLIDATION.

One difficulty which hinders the acceptance of the new views of metamorphism at Malvern is the sound condition of the gneissic rocks. It is unnecessary to repeat here what I have said in Section III. on decomposition and reconstruction. Most of the minerals of the gneiss are sound and clear, because they were newly formed during the metamorphism, and have not since been crushed. Their reconstruction involves a more or less complete fusion of the rock. This is a demonstrable fact where the fragments of crushed felspar are squeezed out into lenticles and coalesce with each other, as in the sericite-gneiss of Ragged Stone Hill (p. 411), and is a matter of fair inference wherever there is a clear passage between crushed diorite and a sound gneiss.

X. SUMMARY.

It will be convenient to bring together the chief results of my five years' work at Malvern, as expounded in the present series of papers.

1. All the crystalline schists of Malvern have been elaborated out of plutonic igneous rocks, chiefly out of a binary granite and two varieties of diorite.
2. The schist-making process has been confined to certain bands (shear-zones), within which the rocks have been subjected to great compression, the mechanical effects produced varying between slight crushing and a pronounced shearing-movement among the constituents, the two extremes shading imperceptibly into each other.
3. The bulk of the rocks had consolidated before the chief pressures set in. During the metamorphism, partial fusion, resulting in plasticity, took place. This effect is found so often to occur where the shearing is at its maximum, while the adjacent rock is merely a crushed solid, that the generation of heat by the shearing-process becomes a probable inference.
4. A crushed diorite, in course of transformation into a mica-gneiss, sometimes passes through the intermediate state of a laminated grit, which thus simulates a true sediment, the subsequent stages of alteration and cementation resembling the process of metamorphism in some bedded rocks.
5. The chief mineral and chemical changes took place where diorite was interlaced with numerous granite-veins, the effects produced in the diorite being due partly to the shearing, partly to the action of mineral solutions.
6. The massive rocks pass into schists through a process of decomposition, followed and partly accompanied by a process of reconstruction, the newly-generated quartz and felspar in the secondary consolidation crystallizing, the former always, the latter frequently, in a granular form.
7. The chief mineral changes affecting the schist-making process

are the replacement of orthoclase by quartz and muscovite, of plagioclase by quartz and muscovite, of chlorite by biotite and white mica, and of biotite by white mica. The reconstruction of felspar is also a prominent feature in the metamorphism.

8. The granite and diorite have often transferred to each other some of their alkaline bases, so that the diorites often locally show an unusual amount of potash, which has been largely used in the production of the micas. The liberation of potash from the granite is (at least sometimes) accompanied by silicification of the veins and the production of garnets.
9. In the metamorphosis of diorite into a muscovite- (or sericite-) gneiss, lime is removed readily, and magnesia more slowly. The persistence of alumina and the elimination of lime and magnesia favour the formation of white mica, which appears to be one of the ultimate products of the schist-making process.
10. In the conversion of diorite into a gneissoid quartzite, alumina and alkalis are removed, as well as lime, magnesia, and iron.
11. Chlorite and iron oxide, produced by the decomposition of diorite, may be infiltrated into the cracks and cleavage- (or shear-) planes of crushed granite, and may migrate to a considerable distance from the contact with the diorite, thus giving rise to an interfoliation of chlorite and biotite with the quartz, felspar, and muscovite of the resulting gneiss.
12. The schists produced by the means here described are divisible into two groups:—(1) Simple schists, formed from one kind of rock, such as biotite-gneiss, mica-schist, sericite-gneiss, muscovite-gneiss, and hornblende-gneiss. (2) Injection-schists, formed from more than one kind of rock, frequently with a banded structure, divided into (*a*) schists of primary injection, the injected material being an intrusive rock—examples are duplex diorite-gneiss, granite-diorite gneiss, and biotite-gneiss; and (*b*) schists of secondary injection, the injected matter being products of secondary decomposition—the chief varieties are chlorite-gneiss, biotite-gneiss, and biotite-muscovite gneiss.

DISCUSSION.

The PRESIDENT said that the Author was to be congratulated on the completion of his triple memoir on the Malvern Hills. He had brought before the Society an ingenious and bold hypothesis, which involved metasomatism on a large scale. He (the President) did not feel qualified to express an opinion on the intricate subject of dynamo-metamorphism, but he supposed that the crushing of rocks in Nature's mortar might increase solubility and facilitate chemical change. There appeared to be two schools of chemical geologists at present—one believing that rocks could not be materially changed in composition, the other accepting very great modifications. There was one very important feature about this paper: it was illustrated by many chemical analyses.

Prof. BONNEY stated that in Dr. Callaway's leading conclusions as to the genesis of the Malvern rocks he agreed, viz. that largely, if not wholly, they were igneous rocks, gneissoid from pressure; but in some details he could not follow him. He failed to understand how, if magnesia were removed from a rock, the alkalis, as indicated in Dr. Callaway's analyses, remained constant when almost everything else was changed. He could not believe in such a change as the formation of a quartzite from a gabbro, referred to by Dr. Callaway; and he had never seen anything to confirm the idea that biotite was formed out of hornblende by way of chlorite. How were you to add silica and alkalis, and get rid of the water? Generally biotite came direct, either from the crushing or from the melting of feldspar and hornblende together.

Mr. HARKER found difficulty in understanding some of the chemical changes which the Author believed the Malvern rocks to have experienced, such as the removal of alumina while the alkalis remained practically undiminished. He asked whether the field-evidence would not allow some of the supposed transitions to be explained by the intrusion of one rock into another.

Mr. RUTLEY agreed with Dr. Callaway, to some extent, in believing that the schists of the Malvern Hills had been formed from plutonic rocks; but he differed from him as to the way in which they had been formed. He had, indeed, already expressed the opinion that they had resulted, in part at least, from the denudation of an old land composed both of eruptive rocks and sediments. With regard to the corroded character of feldspars in the proximity of shearing-zones, he pointed out that the most corroded feldspars which he had met with in the range occurred in a rock which he had described as 'eukrite,' and in which there was no indication of shearing. The acceptance of some of the Author's statements concerning the genetic sequence of minerals demanded the exercise of faith. It appeared that some of the minute bands occurring in biotite-gneiss, which the Author termed granitic, might merely be the result of mineral segregation. On the whole, he considered that the paper dealt with many interesting questions, and, although the conclusions so boldly expressed in it differed from his own, the perseverance displayed by Dr. Callaway in this, as in his previous communications to the Society, rendered his work deserving of very careful consideration.

Prof. HULL wished that the Author had given some better evidence as regards, at least, one point connected with the metamorphism of the Malvern minerals—namely, the conversion of chlorite into biotite. In all his experience amongst metamorphic and igneous rocks he had never noticed chlorite otherwise than as a decomposition-product; whereas biotite was a primary mineral, as shown by its occurrence in modern lavas. He very much doubted the formation of biotite in the manner stated by the Author.

The AUTHOR, in reply to Prof. Bonney, said that the loss of alumina in the change from diorite to gneissoid quartzite was accompanied by a decrease in the alkalis, though perhaps he had not

made that point clear in his hasty summary of a long paper; this change was shown by the study of numerous sections and specimens, which demonstrated an unbroken passage between the two extremes; and the potash for the conversion of chlorite into biotite was supplied by the adjacent granite, while the iron was furnished by the decomposition of the hornblende of the diorite.

To Mr. Harker he replied that the gradations described were shown by very exhaustive enquiry in the field, as well as by microscopic slides.

In answer to Mr. Rutley's observations, he pointed out that corrosion was not necessarily connected with schist-making, but as a matter of fact it was so in the Malvern area. The distinction between primary and secondary injection was not hypothetical, but was based upon clear evidence. The banding of diorite by granite-veins took place on a large, as well as upon the small scale; and the grit of Ragged Stone Hill was not sedimentary, but could be traced into crushed diorite.

In reply to Prof. Hull, the Author remarked that the conversion of chlorite into biotite, asserted by him in 1889, had been confirmed by the researches of Salomon, Lossen, Rüdermann, and other foreign observers.

In conclusion, the Author stated that his views, however heretical they might appear to some of the speakers, were based upon six or seven years' careful work in the field, the cabinet, and the laboratory; and he asked that his paper and his specimens should be studied, before a decided opinion was formed by his critics.