

30. SUPPLEMENTARY NOTES *on the METAMORPHIC ROCKS around the SHAP GRANITE.* By ALFRED HARKER, Esq., M.A., F.G.S., and J. E. MARR, Esq., M.A., F.R.S., Sec. G.S., Fellows of St. John's College, Cambridge. (Read April 26th, 1893.)

[PLATE XVII.]

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I. INTRODUCTION.

In a paper presented to this Society two years ago we described at some length the phenomena of metamorphism exhibited by the various volcanic and sedimentary rocks around the Shap Granite.<sup>1</sup> Since that time re-examination of some of the rocks, in the light of what we have seen in other parts of the Lake District, has enabled us to make certain corrections and additions to our work; and we now offer these with the intention of rendering the description of the metamorphism in some measure more complete.

The chief correction we have to make relates to the volcanic rocks on the northern side of the granite, which we formerly classed with the intermediate rocks (andesitic lavas and ashes) seen to the west of the granite. We now find that they constitute a distinct group of more basic composition. To such a conclusion, indeed, we should have been led by the low silica-percentages of some metamorphosed specimens from Low Fell,<sup>2</sup> a fact which we contented ourselves with recording as inexplicable on the supposition that the rocks had been originally similar to the Stockdale andesites. We have since learnt that basic lavas are very widely distributed over the Lake District, and that the rocks on the northern side of the Shap Granite must be placed in this division. They may with propriety be named basalts, although, on account of the absence of olivine, some petrographers would prefer to call them basic andesites. Since our description of the metamorphosed intermediate rocks was founded on a traverse along a definite line of strike through Sleddale Pike, it is not materially affected by this correction of the mapping; but two or three features which we noted incidentally as of exceptional occurrence in the metamorphosed andesites were really observed in the rocks to the north. These will be pointed out in the brief description which we now proceed to give of the metamorphism of the basic rocks.

<sup>1</sup> Quart. Journ. Geol. Soc. vol. xlvii. (1891) p. 266.

<sup>2</sup> Namely, 50.75 and 50.90, *ibid.* p. 300.

## II. METAMORPHISM OF THE BASIC ROCKS.

In their non-metamorphosed state the basic lavas of this district differ from the intermediate lavas chiefly by being richer in porphyritic feldspar, and that of a basic variety. As other characteristic features, we may note in some examples the somewhat greater abundance of iron ores and the presence of a rhombic as well as a monoclinic pyroxene. The rocks have undergone to a considerable extent the ordinary changes included under the term 'weathering.' Of the resulting secondary products some (bastite, kaolin, etc.) have remained as pseudomorphs of the minerals which generated them, while others, more soluble, have become disseminated through the mass of the rock, and especially collected in small fissures and in the vesicles with which the lavas abound. It is essential to bear in mind that these changes were effected prior to the metamorphism. We hope in a future paper to describe, from another part of the Lake District, the thermal metamorphism of comparatively fresh basic lavas and ashes. In the ashes accompanying the basic lavas of Shap Fell the weathering-products are more uniformly distributed, and metamorphism has developed fewer peculiarities; indeed, these rocks do not differ so much from the andesitic ashes as to demand special attention. (See Pl. XVII. fig. 5.)

Another change which the rocks under consideration have undergone, though not universally, is that resulting in cleavage. This is, as might be expected, most marked in the ashes, and seems to have often determined the direction of the foliation which these show when highly metamorphosed. Locally the lavas have also been crushed, though in less degree. The cleavage clearly preceded the metamorphism, and it is equally clear that it was itself preceded by the processes which filled the vesicles of the lavas with weathering-products. It is interesting to note how, in one and the same specimen, those vesicles which were occupied only by soft materials were completely flattened, while those filled with quartz successfully resisted deformation [760].<sup>1</sup> This feature is to be seen in many parts of the Lake District, and has been remarked by Sir Archibald Geikie.<sup>2</sup>

The first clear signs of metamorphism are seen on Low Fell at a distance of 1150 or 1200 yards from the granite, and, as usual, in the decomposition-products of the rock. One slide shows little streaks of minute flakes of brown mica, with an occasional small crystal of sphene [1279]; in others from the same neighbourhood green hornblende, also accompanied by sphene, occurs almost to the exclusion of the mica [759, 760]. Nearer to the granite the changes increase progressively, those in the contents of the vesicles and small fissures being in advance of those in the body of the rock. The most altered examples always consist entirely of minerals produced in the metamorphism, and present the clear, fresh appearance which seems to be so characteristic.

<sup>1</sup> The numbers in square brackets are those affixed to the slides in the collections of the Woodwardian Museum, Cambridge.

<sup>2</sup> Pres. Addr., Quart. Journ. Geol. Soc. vol. xlvii. (1891) *Proc.* p. 140.

In describing the metamorphism of the andesites, we have remarked that, of the coloured silicates, the one most usually produced is brown mica, hornblende being mostly confined to particular streaks and veins and to the interior of the vesicles, where some accumulation of calcite would favour the formation of a lime-bearing mineral. The basic lavas, as appears from Mr. Garwood's figures,

	Andesite, <i>West of Wasdale Pike.</i>	Basic Lava, <i>Low Fell.</i>	Basic Ash, <i>Low Fell.</i>
SiO <sub>2</sub> .....	59·95 per cent.	50·75 per cent.	50·90 per cent.
CaO .....	3·95 per cent.	10·50 per cent.	3·80 per cent.

are much richer in lime, and accordingly we find green hornblende more common than mica, in the body of the rock as well as in the contents of the vesicles. The ashes associated with the basic lavas, however, have brown mica far more abundantly than hornblende, and the reason for this is seen in the low percentage of lime which they contain.

The mode of distribution of both hornblende and mica in the metamorphosed basic lavas points to these minerals having been formed largely by reactions among the weathering-products, such as the chloritoid substances, calcite, and kaolin; but some of the knots and patches doubtless represent remnants of pyroxene not destroyed by weathering.

In place of, or in addition to, the hornblende, we not infrequently find a colourless pyroxene with good prismatic cleavage and the optical properties of an augite. The occurrences mentioned as exceptional in our account of the andesites belong properly to the basic group. The mineral seems to be identical with the dominant pyroxene of the metamorphosed Coniston Limestones. It is usually found in narrow veins, associated with epidote [759], and within the larger vesicles [1614, etc.].

Epidote occurs abundantly, in more or less perfect crystals and in granular aggregates. The small grains show a pale yellow tint with feeble pleochroism, but in the larger crystals the pleochroism, changing from yellowish green to colourless, is quite vivid. Zonary growth is often indicated by the interior of the crystal showing stronger absorption than the margin. The two leading cleavages are usually evident, and when the crystals are well-bounded the habit is normal [1614, etc.]. We formerly noted epidote in the andesites of Little Saddle Crag, some 1350 yards from the granite-boundary, but, as the mineral was not found nearer the granite, we doubted its connexion with the metamorphism. In the basic lavas there is no room for doubt on this point, and the mineral is found as an accompaniment of very considerable metamorphism, though not close to the granite-junction. It is characteristically found among the contents of the larger vesicles, but occurs also in certain veins and in the general mass of the rock, where it appears to replace felspar [900, from Howe Gill]. The metamorphic origin of the epidote is evident from its mode of association with the

pyroxene, garnet, etc., and the way in which epidote-crystals enclose bundles of actinolite-needles [1750, 1747]. (See Pl. XVII. figs. 2 and 4.)

Sphene, in small quantity, is widely distributed, usually building small crystals of the usual habit, but imperfectly developed. It has a pale brown tint in slices, with feeble pleochroism, never showing, so far as our observations go, the purplish colour and strong pleochroism of the sphene in the metamorphosed andesites. (See Pl. XVII. fig. 4.)

The iron ores of these rocks are magnetite and probably ilmenite, besides pyrites. It is not in every case easy to judge how far the first two can be regarded as metamorphic minerals, but we may fairly assume that, in the most highly altered rocks at least, the original iron ores have undergone complete reconstruction.

In all the most metamorphosed of the basic lavas a large part of the mass consists of a very finely granular mosaic, perfectly clear and colourless, which must represent in a general way the felspathic constituent of the original rock, in so far as that was not decomposed, and its elements worked up into silicates of different type. In the porphyritic feldspars we can trace the progress of a recrystallization, which begins with the original turbid crystals and ends with clear granular aggregates retaining nothing of the original except its outline. The clear mosaic in the matrix is probably in a great measure similar to this. There is little indication of crystal form, and usually no twinning. It is quite possible that quartz may form part of this mosaic. At least, that mineral is easily recognized in separate patches, which probably represent the silica liberated by weathering and recrystallized during the metamorphism. The similar quartz which, in larger patches, figures constantly inside the vesicles has clearly been recrystallized in the processes of metamorphism, as appears from its relations to the associated minerals.

The metamorphism of the amygdules or infilled vesicles, which occur more or less plentifully in most hand-specimens of the lavas, requires special notice. The contents of the smaller vesicles, from 1 inch in diameter down to much less dimensions, have usually given rise to a mixture of green hornblende and quartz. In the smallest quartz predominates, in those which are a little larger hornblende, the quartz often surrounding it as a border, although these relations are not constant [1613, etc.]. The phenomena differ little from those of the similar vesicles in the andesites, except in the occasional presence of other minerals, such as granular sphene [760], epidote, or scattered irregular granules of a light brown garnet [900, from Howe Gill].

In some localities, however, as upon the northern bank of Long-fell Gill, these basic lavas enclose amygdules of exceptional size, up to 2 inches or more in length. In some cases the elongated form due to a flowing movement of the lava has been further accentuated by deformation, the rocks giving evidence of cleavage [1614]. As seen on a surface of the rock freshly broken these larger vesicles

often present one or more shells of compact appearance and pale colour, while the interior is occupied by a confused crystalline aggregate of dark hornblende with an occasional patch of pyrites. In slices the paler portions are found to consist chiefly of quartz and epidote, with a little actinolite or hornblende, most of the hornblende occurring in the dense patches of imperfect crystals which are so conspicuous to the naked eye. The augite already mentioned also occurs. But the most interesting feature is the preservation in the centre of these large vesicles of some remnants of calcite, a mineral never left undestroyed in the smaller ones or in the body of the rock. The calcite is in crystalline patches moulding or enclosing the other minerals mentioned, and, in particular, it is often penetrated by fringes and brushes of slender needles of actinolite [1614]. From this it is evident that the carbonate, though not decomposed, has been recrystallized at the time of the metamorphism.

The most interesting specimens come from a large block which was not found in place, but must belong to a locality very near the last mentioned. This rock, besides smaller vesicles, has others of unusually large size, often 2 inches in diameter, and the metamorphism of their contents has given rise to some curious features. Hand-specimens show the usual quartz, epidote, and green hornblende, the last less abundant than is ordinarily the case, with occasional specks of pyrites and some residual calcite; but the most prominent mineral in all the largest vesicles is a deep-brown garnet in crowded groups of small crystals, or in larger crystals sometimes  $\frac{1}{4}$  inch in diameter. The colour and lustre are those proper to the lime-iron-alumina garnets. The faces of the rhombic dodecahedron are often well developed, especially when the mineral is moulded by calcite, and the broken crystals show the concentric shell-structure which is so frequent a character in garnets produced in thermometamorphism.

In thin slices [1747-1752] the garnets vary in colour from a rather light brown to a very pale tint. Zones of growth are often indicated, either by differences of colour in successive layers or by the accumulation of impurities along the surfaces which divide them, and in this way the dodecahedral form may be seen even when the crystals are so closely clustered as to prevent the development of bounding-faces (see Plate XVII. fig. 3). The recognizable inclusions are calcite, epidote, quartz, hornblende, augite, and sphene, but these are only wedged in between garnet-crystals, not really enclosed. Most of the garnets examined are strictly isotropic, or give but very indistinct glimpses of illumination when rotated between crossed nicols. Some, however, show marked double refraction [1749], the phenomena being very similar to those described in the idocrase-garnet rock of Wasdale Head (*op. jam cit.* p. 312). The polysynthetic twinning on the 'rhombic-dodecahedron type' of Klein,<sup>1</sup> and the numerous concentric zones differing in birefringence, are well exhibited. Here, however, the doubly-refracting crystals are found in juxtaposition with others of closely

<sup>1</sup> 'Optische Studien am Granat,' Neues Jahrb. 1883, vol. i. pp. 87 *et seq.*

similar appearance, which have no action on polarized light, or the interior of a crystal is seen to be birefringent, the marginal portion isotropic. The converse relation, described by Wichmann<sup>1</sup> as occurring in the rocks of Berggiesshübel and Schwarzenberg in Saxony, we have not observed, but a shell of doubly-refracting sometimes occurs within a shell of singly-refracting garnet, and encloses a kernel which is very nearly isotropic. The absorption-colour, presumably connected with the relative proportions of lime and ferrous oxide in the mineral, does not seem to stand in any very evident relation with the optical anomalies, but it may be noted that we have not found birefringence in the more deeply coloured, and so more ferriferous, variety.

As a curious illustration of the facility with which lime-garnets are produced in connexion with thermal metamorphism, we may be permitted to cite a literally far-fetched example. It occurs among the rocks collected by Mr. J. J. Lister from the Tonga Islands. The island of Mango<sup>2</sup> consists, above sea-level, entirely of volcanic tuffs and breccias, but these are presumed to rest upon an old coral-reef, and fragments of coral, some 6 inches in diameter, are found mingled with blocks of lava, etc., among the volcanic ejectamenta. Although these corals preserve perfectly their characteristic structures, the interstices are completely occupied, in the specimens examined, by crystalline garnet, doubtless grossularite. The mineral is colourless in thin slices, and though, from the nature of the case, there are no external crystal-faces, the birefringence, the polysynthetic structure, and the concentric zones are beautifully exhibited [1274, 1331].

In addition to the minerals already named, these metamorphosed vesicles show under the microscope a colourless augite, granules of felspar (?), patches of magnetite, and occasional crystals of sphene. An examination of the manner in which the several minerals mould or enclose one another proves that they have generally followed a definite order of crystallization, which is not often departed from. The order is—iron ores, garnet, sphene, augite, green hornblende and actinolite, epidote, quartz, calcite. So far as it goes, this bears a close resemblance to the normal order of consolidation of minerals from igneous fusion, as expressed in Rosenbusch's 'law of decreasing basicity.' The iron ore in the centre of the vesicles is often pyrites, that near the edge magnetite or some other black ore. The little patches of green hornblende are most plentiful near the margin, where they are associated with a finely granular mass which seems to be felspar. The epidote is most abundant, as a rule, in the marginal portion of the large vesicles, while the calcite and the best-developed garnets are found in the central portion. Many of the minerals, however, show a rather intricate commingling. The augite forms either crowds of little imperfect crystals or larger crystal-plates, in the latter case after enclosing a quantity of green actinolite or actinolitic hornblende in needles or shreds, intergrown with the

<sup>1</sup> Zeitschr. Deutsch. geol. Gesellsch. vol. xxvii. (1875) pp. 749-751.

<sup>2</sup> Quart. Journ. Geol. Soc. vol. xlvii. (1891) p. 596.

augite with the usual crystallographic relation. The appearances are very similar to those in a common kind of 'uralitization,' but it is almost certain that we are dealing here with an original parallel intergrowth. The amphibole-mineral often projects in a fringe into a contiguous crystal of epidote or calcite, and apparently isolated needles, with the same orientation, lie embedded in the latter mineral. (See Pl. XVII. figs. 2 and 4.)

### III. THE SILURIAN BEDS OF WASDALE BECK.

Leaving the basic lavas, we pass on to some other points. In our former paper we stated that the oldest members of the Silurian were not visible in the Shap district. Since that statement was written we received from Prof. H. A. Nicholson a specimen which induced us to re-examine the Wasdale Beck section.

Prof. Nicholson's specimen is a black mudstone, somewhat hardened, and generally resembling the flags of Wasdale Beck, but blacker and less splintery than those above the junction of that beck with Blea Beck, whence its finder believes it was derived, though, as it has been in his possession for some years, he is not certain that it was obtained *in situ*. It shows every sign of having been altered to the same extent as the supposed Coniston Flags of that locality, and indicates the existence of the *convolutus*-zone of the Skelgill Beds in the Shap district, for it contains *Monograptus communis*, Lapw., *M. convolutus*, His., *M. gregarius*, Lapw., *M. Hisingeri*, Carr., and *Rastrites hybridus*, Lapw. Our re-examination led us to believe that the flaggy beds near the junction of the streams have been correctly referred to the Coniston Flags, but that Stockdale Shales may occur higher up the beck. The matter is not one of importance as affecting our studies of the metamorphic rocks, for the shales of the Stockdale series could no doubt be altered in much the same way as those of the Coniston Flags, but it is of interest to note the probable occurrence of Stockdale Shales in Wasdale Beck, where Prof. Nicholson long ago recorded their existence.

Our re-examination of the section in Wasdale Beck led to the discovery of discontinuous calcareous bands in highly argillaceous rocks, cropping out of rushy ground  $\frac{1}{2}$  mile S.W. of Shap Wells. The calcareous bands yielded an obscure brachiopod, and from the general appearance of the rock we believe that we have here either an exposure of the *glaber*-zone of the Skelgill Beds or else of a portion of the Ashgill Shales, but more probably the former. These calcareous bands will be referred to again.

Some features in the metamorphism of the Silurians of Wasdale Beck, which had escaped our notice, have been pointed out by Mr. Hutchings.<sup>1</sup> He describes garnets as occurring in great numbers in some of the slates, at about the same stage as the development of decided 'spots.' As the crystals do not exceed  $\frac{1}{200}$  inch in diameter, the precise variety would not be easy to determine, but we

<sup>1</sup> Geol. Mag. for 1891, p. 459.



may probably regard them as common garnet. The hornblende-mineral noticed near the same place is perhaps the same as that which we referred to tremolite in the Upper Coldwell Beds at Packhouse Hill.

Another mineral of considerable interest discovered by Mr. Hutchings is sillimanite,<sup>1</sup> which he finds in highly metamorphosed ashes belonging to the rhyolitic group at a distance of 3 feet from the granite-junction. It is associated with andalusite. The sillimanite does not occur in matted patches as at Knocknairling Hill,<sup>2</sup> but in isolated prisms.

#### IV. CONDITIONS ATTENDING THE FORMATION OF SECONDARY FELSPAR-CRYSTALS.

In our former paper (*op. jam cit.* p. 297, pl. xi. fig. 6) we recorded an instance of feldspar-crystals occurring, in association with brown mica, inside the vesicles of one of the metamorphosed andesites. This we regarded as an exceptional effect of the metamorphism, and were obliged to leave unexplained. We have since learnt that clear crystals of feldspar, both monoclinic and triclinic, occur within the vesicles of lavas which have never been subjected to such metamorphosing influences as those due to the Shap Granite. Mr. Hutchings<sup>3</sup> has observed numerous cases in the Lake District, and the same thing occurs in the Cross Fell Inlier.<sup>4</sup> These instances certainly seem to prove that, with proper conditions, feldspars may be formed inside vesicles without the co-operation of either high temperature or exceptional pressure. The case near the Shap Granite may well fall under the same head. The purity of the crystals, and the manner in which they are moulded by the brown mica accord with the supposition that the feldspar was crystallized in the vesicle prior to the metamorphism. The apparent rarity of the phenomenon is another confirmation of the idea, for while a striking regularity is observable in the undoubted effects of thermal metamorphism around the granite, the formation of feldspar under ordinary conditions of temperature seems to be quite capricious. The remarkable freshness of the Shap metamorphic rocks precludes the third alternative, that the feldspar was formed subsequently to the metamorphism. It may be pointed out that, the available lime within these vesicles being used to make feldspar, the coloured silicate produced in the metamorphism was a brown mica instead of the usual hornblende.

The formation of feldspar in rocks quite independently of the special conditions usually connoted by the term 'metamorphism' is a subject which deserves further investigation. Veins largely composed of clear crystalline feldspar fill cracks in some of the Dartmoor diabases,<sup>5</sup> and among acid rocks we have noticed a similar

<sup>1</sup> See also Mr. Barrow's paper in this number of the Quarterly Journal, especially pp. 337-338.

<sup>2</sup> Miss Gardiner, Quart. Journ. Geol. Soc. vol. xlvi. (1890) pp. 575 *et seqq.*

<sup>3</sup> Geol. Mag. for 1892, p. 224.

<sup>4</sup> Harker, Quart. Journ. Geol. Soc. vol. xlvii. (1891) pp. 514, 515.

<sup>5</sup> *Id.* Geol. Mag. for 1892, p. 346.



occurrence in some old rhyolites and ashes from Malvern, collected by Mr. J. F. Bryant. If such processes are possible within the mass of a rock, as well as in vesicles and fissures, some peculiarities which have been ascribed to dynamic metamorphism may be found to admit of a different explanation. The rock described by one of us from Wythwaite Top in the Cross Fell Inlier is a case in point.<sup>1</sup>

#### V. THE METAMORPHOSED CONISTON LIMESTONE BEDS OF WASDALE HEAD.

In describing the highly metamorphosed members of the Coniston Limestone group at Wasdale Head we showed that, although pure lime-silicates, such as wollastonite, are not wanting, the more common minerals are augite, tremolite, etc., and an analysis yielded a noteworthy amount of magnesia. Since the supposition that this or any other constituent was introduced during the metamorphism was opposed to all our results, we suggested that the rocks had been partially dolomitized before the intrusion of the granite (*op. jam cit.* p. 315). To put this to the test, we have re-examined the non-metamorphosed rocks of Blea Beck. In the case of the more ashy beds it is not easy to form any conclusion, but the purer strata exposed in the beck give clear evidence of partial conversion to dolomite. One bed in the Upper Coniston Limestone, for example, consists of a pale brown, finely granular matrix enclosing pure white crystalline patches up to  $\frac{1}{4}$  inch in diameter. The specific gravity 2.796 indicates the presence of both calcite and dolomite in the rock, and (allowing for the few quartz-grains which are the chief impurity) the two carbonate minerals must be present in roughly equal quantities. The white patches are unaffected by dilute acid, and consist of clustered rhombohedra of unusually pure dolomite [1616]. The greyish-brown, finely granular portion of the rock effervesces with dilute acid, and must be chiefly calcite; but, as it makes up quite  $\frac{3}{4}$  of the total bulk, it would appear that there is some admixture of dolomite in it.

The various types of lime-silicate rocks which we have described at Wasdale Head all belonged to the more impure portions of the Coniston Limestone group, representing the metamorphism of calcareous ashes and shales rather than of true limestones or dolomites. Further search, however, shows that the latter are not entirely wanting at that locality, and that they present an instructive contrast with the less purely calcareous members of the group. They illustrate what seems to be a general law, that the carbonates are not decomposed in thermal metamorphism unless silica in some available form be at hand to replace the carbonic acid. A bed forming part of the Lower Coniston Limestone, and evidently representing one of the purer layers in that formation, is converted into what is essentially a grey saccharoidal marble, the calcite having apparently, for the most part, recrystallized without further change. This is within 100 yards of the granite-junction and close to the rocks formerly described, which have been converted into aggregates of idocrase, garnet, wollastonite, etc., with total elimination of their carbonic acid. Further,

<sup>1</sup> Harker, Quart. Journ. Geol. Soc. vol. xlvii. (1891) pp. 515, 516.

in the relatively pure limestone now noted, the formation of lime-silicates, etc., has gone on wherever impurities were collected. While the greater part of the rock consists of rather finely crystalline calcite (perhaps with dolomite), the hand-specimens show little streaky patches which are harder than the rest and give no effervescence with acid. Of these little patches some are of a greenish tinge and are probably augite, others have the characteristic lustre and brown colour of idocrase, while others again are white and apparently feldspathic. We also remark, scattered through the mass, little granules of a black iron ore and of a yellow pyrites.

Another feature of this rock, doubtless connected with the nodular structures so prevalent in the purer portions of the Coniston Limestone group, is the occurrence of distinct ovoid nests of lime-bearing silicates with a definite arrangement of nucleus and outer shell. The nucleus consists of brown crystals of idocrase [1427, 1428], often 1 inch in length, disposed in stellate groups; the outer part of the nest, forming a shell  $\frac{1}{2}$  to 1 inch in thickness, is of a white crystalline mineral which proves to be chiefly a plagioclase-felspar [1746]. The mineral forms striated crystal-plates considerably larger than any yet observed in these limestone-rocks. Associated with it are specks of a brightly-polarizing pyroxene and grains of iron ore, the former becoming more abundant where the feldspathic nodule meets the matrix of calcite. (See Pl. XVII. fig. 6.)

#### VI. SOME CONCLUDING CONSIDERATIONS.

In conclusion we would venture on one or two remarks which, following out ideas suggested in the foregoing notes, may be found to have a more general bearing. All that we have seen in the Shap district confirms the belief that thermometamorphism is not in general accompanied by any change in the chemical composition of the rocks affected. The exceptions we have already noted: namely, the (partial) loss of water and the expulsion (under proper conditions only) of carbonic acid.<sup>1</sup> These do not seriously modify the law in question. We have, however, gone farther in applying this law not only to the metamorphosed rocks as a whole, but also to any small portion of any of these rocks. In the course of our descriptions we have seen innumerable facts which point to the conclusion that no transference of material has taken place within the mass of the rocks except between closely adjacent points. If this be, as we believe, a general law, it follows that the mineral produced by complete thermal metamorphism at any point of a rock depends upon the chemical composition of the rock-mass within a certain small distance around that point.<sup>2</sup> The question naturally arises, what is the radius of this sphere of influence? Can we form any estimate of the maximum range at which interchange of material takes place between points in the interior of a rock undergoing thermal metamorphism?

The distance in question will presumably not be the same for

<sup>1</sup> In some districts we should have to allow other exceptions for rocks in the neighbourhood of an acid intrusion: namely, the introduction of boric and hydrofluoric acids.

<sup>2</sup> Comp. Harker, Bull. Geol. Soc. Amer. vol. iii. (1891) p. 20.

different chemical substances, and we must also expect to find it greater at higher temperatures; but we may at least arrive at some idea of its order of magnitude by considering some one case. The case which is most easily discussed is the production of lime-silicates at the expense of calcite. The carbonate is decomposed, as we have remarked, only in presence of silica or of some silicate from which silica can be disengaged, and, given this condition, the process is one that can be effected at a comparatively low temperature. Now, in the amygdaloidal basic lavas we have pointed out that the calcite in the centre of the largest vesicles is never destroyed, although it has recrystallized during the metamorphism, and free quartz has recrystallized in the surrounding rock and in the marginal parts of the same vesicles. Between the residual calcite and the quartz various lime-bearing silicates are interposed. The calcite is preserved only in the centre of the largest vesicles, smaller ones in the same rock being occupied by silicate minerals, quartz, etc. In the examples we have more particularly studied calcite is never preserved within less than  $\frac{1}{4}$  inch of the boundary of the vesicle, and this gives a first approximation to the distance we are seeking. It is, however, a maximum estimate, and is doubtless too great, for the vesicles before metamorphism were not always occupied by calcite alone. If we measure the distance between calcite and quartz which have recrystallized within the same vesicle, we shall reduce our estimate considerably: perhaps  $\frac{1}{20}$  inch would be nearer the mark for the distance to which the interchange of lime and silica has demonstrably taken place in the production of lime-silicates. Similar evidence is furnished by certain flat calcareous nodules noted above in the metamorphosed Silurians of Wasdale Beck, belonging probably to a faulted lenticle of Stockdale Shales (*Phacops glaber*-zone). Here the calcite often remains in the centre of a nodule, the marginal part being always converted into an aggregate of pyroxene and other silicates. This border is often  $\frac{1}{8}$  inch thick; but if, to allow for impurities in the nodules, we take the least thickness, we obtain as before about  $\frac{1}{20}$  or  $\frac{1}{25}$  inch. The distance from the granite—and so presumably the temperature of metamorphism—is not very different from that for the former locality.

The same question might be approached from another side, by examining the size of the individual crystals or groups of metamorphic minerals where their production has been dependent on the heterogeneous nature of the rocks metamorphosed. The clusters of brown mica produced in some of the ashes around grains of original magnetite are an example. Here, however, we have to exclude such minerals as contain numerous inclusions, either of other metamorphic products or of unchanged material. It is not easy to arrive at any quantitative results, but the impression gained by a study of specimens is in general accord with the foregoing conclusions.

We may add that the dependence of the range of transference of material upon the temperature attained during the metamorphism is well illustrated in the calcareous ashes of the Shap district. On the outer edge of the metamorphic aureole only the most finely divided calcite has been decomposed.

# 370 METAMORPHIC ROCKS AROUND THE SHAP GRANITE. [Aug. 1893.

The spotted slates and ashes which we have described, where the spots are spaces relatively free from brown mica (*op. passim cit.* pp. 307, 319), may be taken as positive evidence of the transference of ferrous oxide from point to point in the rocks. The radius of the spots is not more than about  $\frac{1}{20}$  inch, a distance similar to that found for the interchange of lime and silica.

## VII. LIST OF METAMORPHIC MINERALS OF THE SHAP DISTRICT.

We append a revised list of the metamorphic minerals noticed in the Shap district, but such a list cannot of course claim to be exhaustive. It has been shown that basic, intermediate, and acid lavas and ashes, as well as pure and impure limestones, slates, and grits, all come within the metamorphic aureole, and further that the results were often modified by the effects of meteoric agencies prior to the intrusion of the granite. In the great variety of phenomena resulting from such conditions, it is probable that many points of interest remain still untouched.

	Basic Lavas and Ashes.	Intermediate Lavas and Ashes.	Acid Lavas and Ashes.	Calcareous Rocks.	Argillaceous Rocks.
Quartz .....	*	*	*	*	*
Orthoclase .....	.....	*	*	*	*
Plagioclase (various) .....	*	*	*	*	*
White Micas .....	.....	.....	*	.....	*
Brown Micas .....	*	*	*	*	*
Chlorites .....	*	.....	.....	.....	*
Tremolite .....	.....	.....	.....	*	*
Actinolite .....	*	*	.....	.....	.....
Green Hornblende .....	*	*	(*)	.....	.....
Wollastonite .....	.....	.....	.....	*	.....
Lime-augite .....	*	.....	.....	*	.....
Epidote .....	*	*	.....	.....	.....
Idocrase .....	.....	.....	.....	*	.....
Lime-garnet (isotropic) .....	*	.....	.....	*	.....
Lime-garnet (birefringent) .....	*	.....	.....	*	.....
Common Garnet .....	.....	.....	.....	.....	*
Tourmaline .....	.....	.....	(*)	.....	(*)
Sphene .....	*	*	.....	*	.....
Rutile .....	.....	.....	*	.....	*
Anatase .....	.....	.....	.....	.....	*
Ilmenite .....	*	.....	*	.....	*
Magnetite .....	*	*	*	(*)	*
Pyrite and Pyrrhotite .....	*	*	*	*	*
Apatite .....	.....	(*)	*	.....	.....
Andalusite .....	.....	.....	*	.....	* ?
Disthene or Cyanite .....	.....	.....	*	.....	.....
Sillimanite .....	.....	.....	*	.....	.....
Calcite and Dolomite .....	(*)	.....	.....	*	.....
Graphite .....	.....	.....	.....	.....	* ?

## EXPLANATION OF PLATE XVII.

*(The figures are all drawn in natural light and magnified 20 diameters. The numbers in brackets [ ] refer to the slides.)*

- Fig. 1. [1748] Portion of a large amygdule in a loose block of metamorphosed basic lava, north of the granite mass. In the upper part of the figure is a large crystal of epidote, bounded on the right by clear quartz, on the left by calcite. The latter is penetrated in the lower part of the figure by needles of amphibole, and to the right of this is a plate of augite enclosing grains of epidote.
- Fig. 2. [1750] Another amygdule in the same. In the lower left-hand quarter is a plate of augite with intergrown needles of amphibole. Similar needles, in parallel position, penetrate the calcite which occupies the central part of the figure. Above to the right is garnet, to the left quartz.
- Fig. 3. [1749] Another amygdule in the same. A cluster of garnet-crystals, some showing zonary growth: patches of calcite occur interstitially.
- Fig. 4. [1747] Another amygdule in the same. An intricate admixture of garnet and calcite, the garnet bounded on the right by a large epidote-plate enclosing two imperfect crystals of sphene. Above these is a crystal of augite with parallel intergrowth of amphibole-needles, some of which extend as a fringe into the epidote. Pyrites and quartz are also seen.
- Fig. 5. [896] Highly metamorphosed ash associated with basic lavas, Poorhag Gill; very near the granite. Flakes of brown mica with partial parallel disposition are scattered thickly through a clear, very fine-grained mosaic, essentially of felspar. The relatively clear space marks the position of a felspar-crystal recrystallized into an aggregate of rather less fine texture than the matrix.
- Fig. 6. [1746] Portion of highly metamorphosed Lower Coniston Limestone at Wasdale Head; about 100 yards from the granite. The slide shows part of the light-coloured border of one of the idocrase-nodes in the marble described on p. 368. Striated felspar occurs in relatively large plates, as well as in small grains; with it, in subordinate quantity, is a monoclinic pyroxene; the opaque mineral is apparently pyrites.

## DISCUSSION.

The PRESIDENT congratulated the Authors on this important addition to their previous communication. In some respects this paper was the antithesis of the one which had just been read (Dr. Callaway's), for the Authors limited the area in which metasomatic change took place to a fraction of an inch.

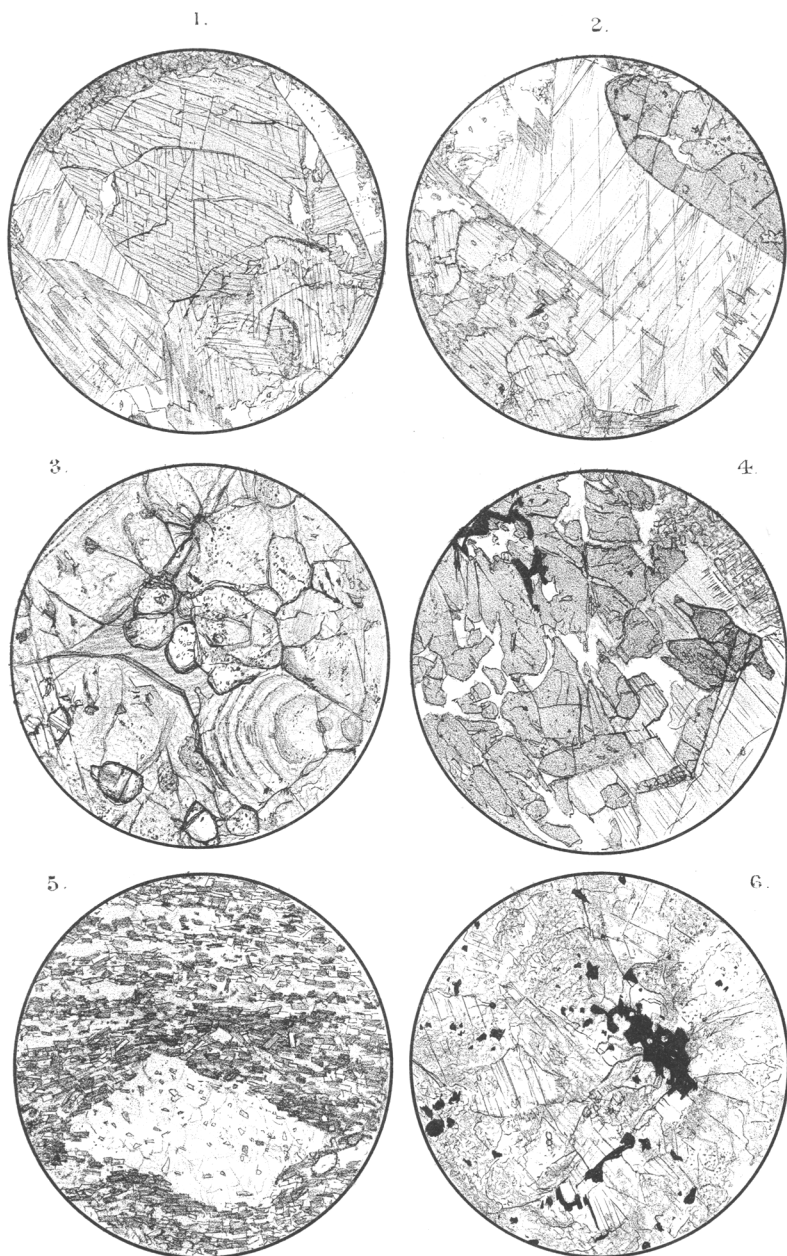
Mr. RUTLEY considered that the statements made by the Authors regarding the development of certain minerals in the altered rocks were of great value. Concerning the absence of reaction between the calcite in the amygdaloids and the silicates which occurred in close proximity, he cited a case in which the molecular rearrangement brought about by the conversion of a piece of flashed glass into a crystalline mass had caused scarcely any disturbance of the coloured film. The statements relating to the development of epidote were important, since, so far as he was aware, that mineral had not yet been artificially reproduced.

Mr. TEALL was especially interested in that portion of the communication which dealt with the change brought about in the calcareous portions of the rocks. The silicates there produced were allied to those found in crystalline limestones associated with gneisses and schists, and the work of the Authors might therefore throw light on the conditions under which these rocks were produced.

Mr. HARKER, in reply to Mr. Rutley, said that the epidote described as occurring in the metamorphosed basic lavas was found chiefly in the outer parts of the large amygdules and in the rock bordering the amygdules. It was undoubtedly a product of thermal metamorphism.

Mr. MARR also spoke.





A. Harker del. F. H. Michael lith.

Mintern Bros. imp.

SECTIONS OF METAMORPHIC ROCKS, SHAP.