6. *On a SECONDARY DEVELOPMENT of BIOTITE and of HORNBLLENDE in CRYSTALLINE SCHISTS from the BINNENTHAL.* By Prof. T. G. BONNEY, D.Sc., LL.D., F.R.S., V.P.G.S. (Read December 7th, 1892.)

PRESSURE is one agent in mineral change. In some cases, as when a shale is converted into a phyllite, the constituents become rather larger, but more commonly the result of oppression is degradation. This is especially true of the crystalline rocks. The effects of earth-movements on granites, gneisses, marbles, mica- and other schists are familiar to all workers in such districts as the Alps or the Scottish Highlands—we might say in almost any great mountain-chain, whatever be its date. Sometimes, indeed, an original constituent has ‘gone through the mill’ comparatively unscathed. Its weaker associates have been crushed to powder, which has acted like a packing-material. But cases occur where new minerals of considerable size are developed here and there from the débris of the original constituents.¹ The greater part of the rock is little more than reconsolidated detritus; it still retains the marks of the *peine forte et dure* to which it has been subjected; but nevertheless it has set up a structure which might be termed porphyritic. The process is analogous to the formation of chiasfolite in contact-metamorphism. The mass of the rock is little changed, but a large mineral has been developed: for the one millimetres, for the other centimetres are appropriate standards of measurement.

Still, so far as my experience goes, this secondary development on an important scale is very rare; commonly when large minerals occur in a catathlastic rock,² as the garnets in certain Alpine schists, or the sablite in the fine-grained limestone of Tisee, they are survivors from the original coarsely crystalline rock. From time to time, however, I have noted instances of this secondary growth, but it generally has been on a very moderate scale. Hence it may be worth while to describe two specimens, which, curiously enough, were received together. Both came from the same neighbourhood, the Binnenthal (Canton Valais), and from the same group of rocks—the dark-mica schists, in which no small part of that valley is

¹ It will be understood that I am speaking throughout of the silicates usually present in crystalline rocks. Such minerals as quartz and calcite form so readily as not to count for much, nor do I refer to the ordinary zeolites, produced in certain igneous rocks. All these, however, seem to require room (*i.e.* occupy cavities), while those of which I speak occur in the mass of the rock.

² Some such word as this is needed to express detrital rock due to crushing *in situ*. ‘Crushed’ would do, but geologists are such excellent Greek scholars that no word has a chance of coming into fashion unless it be derived from that language. ‘Mylonitic’ is doubtfully correct, etymologically speaking, and suggestive of an erroneous idea, for it implies grinding as between revolving millstones. Also it has been generally applied to rock affected by a *shearing* crush, not by a direct crush, as of a press.

excavated. This group, the highest in position among the crystalline rocks of the Alps, practically extends, as I have already stated,¹ from one end of the chain to the other. Its members are usually more or less calcareous, though quartz-schists occur; mica is almost invariably present, but occasionally the rock becomes a marble, practically a crystalline mass of calcite or dolomite. Chloritic and hornblendic schists also occur, but some of these are certainly modified intrusions, though others may have been originally interstratified tuffs. These dark-mica schists are not seldom interbanded with impure quartzite or quartz-schists, just as argillaceous and arenaceous layers are, associated in the Palæozoic rocks of the Isle of Man or of Morlaix,² or in other cases of sediment too numerous to mention, even down to the stratified drifts at Cromer. Not unfrequently, as I have noted in previous papers,³ these dark-mica schists contain garnets, from the size of a small cherry downwards. I have found them myself at intervals from the southern slopes of the Lukmanier Pass to near Binn, a distance of over thirty miles in a straight line. In places, as in the crags at the head of the Ritom Boden (Val Piora), on the Nufenenstock, or in the ridges about the Gries Glacier, these garnet-bearing schists are of no small thickness, but there are considerable intervals in which I have not met with that mineral, and I have not yet found it on the Simplon Pass⁴ or in the Vispthal.

For a description of the structure, macroscopic and microscopic, of these garnet-bearing rocks and other associated schists, I may refer to my paper, already printed in this Journal,⁵ and to an elaborate investigation by Dr. Grubenmann,⁶ frequently quoted therein.

The specimen now to be noticed was collected by Mr. J. Eccles, in the summer of 1890, from the outcrop in the bed of the torrent above the village of Binn.⁷ Above it are schists of the 'Pian Alto' type, which become, somewhat higher up, distinctly calcareous. They are overlain by the white dolomite, mentioned in my former paper (p. 211).

This specimen (a slab about .5 inch thick) differs little from those collected by myself in other localities. The upper and under surfaces are due to cleavage-foliation; the lustre perhaps is slightly more silvery than it is in some of my own specimens, where it more resembles that of graphite. Evidently it is due to a continuous

¹ Quart. Journ. Geol. Soc. vol. xlv. (1890) p. 187.

² *Ibid.* vol. xlv. (1888) p. 11.

³ *Ibid.* vol. xlii. (1886) *Proc.* pp. 72-75; *ibid.* vol. xlv. (1890) pp. 202-3, 224-8.

⁴ It has, however, been found by Mr. J. Eccles not far away to the east, and on the southern side of the watershed.

⁵ Vol. xlv. (1890) pp. 199-204, 208-210, 224-229.

⁶ Mitt. der Thurg. naturf. Gesellsch. 1888, Heft viii.

⁷ We discovered the rock in 1889, but, being quite satisfied as to its nature, we did not bring away a specimen, for some scrambling would have been required to get it, and we had done more than an eight hours' day. But as we did not find this particular rock farther east, I asked Mr. Eccles, in 1890, to be so good as to bring back a specimen.

film of a very minute white mica, forming a kind of 'varnish.' The garnets, about 0·25 inch in diameter, have been affected by pressure—but still retain a fairly regular dodecahedral form. One difference only attracts the eye, most conspicuous on the clean-cut surface, that here and there flakes of biotite (sometimes nearly the above length) occur, often parallel with, but occasionally athwart the direction of cleavage.

The matrix of the rock, when a thin section is examined under the microscope, indicates the effects of severe pressure, and resembles my specimen from the Val Canaria more closely than those from Val Piora. It is like a mass of matted fibres, which lie roughly in one direction. These are flakelets of a colourless mica, among which is scattered much opacite in small rods or plates, down to the most minute dust; the latter has a slightly streaky arrangement.¹ Part of one garnet is on the slide: its margin is rather irregular; the 'sides' of the grain are bounded by a narrow zone of cleaner mica, brown and white. Streaky opacite is continued through the grain, bending slightly out of the usual direction, but is almost absent for a space of nearly ·01 inch from the margin. In the garnets from the other localities lines of opacite can also be seen. Films of biotite also may be noted in the groundmass of these rocks, suggestive of a crystallization of later date than the pressure. In this slide the matter appears to be beyond doubt. Here the biotite occurs in crystalline grains, rarely in scattered films. The basal planes of the mineral sometimes almost lie in the plane of cleavage-foliation, but are often athwart it, and once at right angles to it. The grain is elongated, in the former case, in the direction of the basal plane, when it is nearly free from enclosures; in the latter case the elongation is perpendicular to the basal plane, and the streaks of opacite pass through the mineral, though the quantity seems diminished. The last-named grain, a portion of which is figured (see fig. 1, p. 107), is as nearly as possible ·175 inch long, at right angles to the basal plane. For slightly more than one third of its length, it is about ·03 inch broad. It is then invaded by a streak of matrix, which enters through a gap in one side nearly ·02 inch wide, but part of the crystal forms a continuous strip, though in it the mica for a space almost disappears, as if there had been an insufficient supply of the requisite constituents (the mineral being well developed on either side of the gap). The streaks of opacite pass through the biotite, though in the clearer portions they are diminished in quantity, the finer lines disappearing, but twice or thrice a thin strip of biotite, bounded by two cleavage-planes, interrupts them more or less completely. Generally, however, these planes can be seen to cut right through the 'dusty' streams without producing any effects.

The relations of these biotite-crystals to the matrix seem to place it beyond doubt that they have been completely reconstituted, if not wholly formed, since the epoch when the rock was modified

¹ Other silicates and probably quartz are also present, but as these are unimportant for my purpose I have passed them over.

by pressure. Ought we not to say the same of the garnet? It must be later than the opacite: this material, however, I take to be a very early constituent; it occurs in all my specimens, but with less regularity in those which show most crushing. In some cases a garnet, or part of it, has obviously been pulverized and

Fig. 1.—*Secondary development of biotite in a crushed schist.* $\times 30$.

reconstituted¹; in others the stratulæ of opacite lie in a different direction from those of the matrix. So I think that in the Binnenthal rock the garnet was only slightly compressed, without material fracture, and the stratulæ of opacite, already present, were slightly flattened. But if the biotite-crystal described above had been already formed when severe pressure was applied, it must have bent, zigzagged, or split open, for mica is a mineral 'sensitive' to pressure, and generally retains the marks of maltreatment. So I consider this biotite to be a constituent which appeared late in the history of the rock, though very probably the crystal may be reconstructed from the ruins of a former one. If the rock had been much sheared and its fragments mingled, then scattered films ought to have been produced, as has happened in some of the other instances. Here in all probability the crush was a direct one; still the molecules must have travelled, transverse to the structure of the rock, for some little distance, in order to build up a crystal such as that which has been described.

The next instance of constructive crystalline action seems to me still more remarkable. The specimen was obtained by Mr. J. Eccles on the Hohsandhorn, near the summit (10,515 feet). I have not ascended the peak, but have seen it from the summit of the neighbouring Ofenhorn (10,728 feet) and from a pass (about 9400 feet) over the connecting ridge. This is gneiss, but the peak of the Hohsandhorn is formed of the dark-mica schists mentioned above, which are parted by a zone of marble. The matrix of the specimen,

¹ See Quart Journ. Geol. Soc. vol. xlv. (1888) pl. xv. (Attwood on 'Geology of Mysore') for excellent representations of crushed and flattened garnet. Parts of fig. 1 (the schist), though much more quartzose, give some idea of the 'fibrous' structure referred to in this paper. Both it and fig. 2 represent the mode in which the quartz and biotite get 'mixed up' in another mineral.

macroscopically, resembles generally that of the garnet-bearing schist; it has a similar sheen, but contains, instead of garnets, numerous dark actinolites, rather roughly formed, which are commonly from $\frac{1}{2}$ inch to $\frac{3}{4}$ inch long and about $\frac{1}{10}$ inch thick. These lie mostly in the general direction of the cleavage-foliation, but some make high angles with it. They present a certain resemblance to the still larger green actinolites in the garnet-bearing schist, so abundant on the southern slopes of the St. Gothard *massif*, but in the present case both the mineral and the rock have a 'dirtier' aspect. The matrix under the microscope (allowing for a clear streak mostly occupied by quartz, biotite, and paragonite (?), no doubt a rolled-out vein) does not differ much from that of the ordinary black-garnet schist, except that the quantity of opacite is less, and of quartz more, in proportion to the white mica. But the

Fig. 2.—*Hornblende-crystal (with some biotite) including curved stratulæ of opacite.* $\times 30$.

streaks of opacite often exhibit sharp flexures. Films of biotite occur here and there in parts of the slide, grains and plates of iron oxide, and small narrow prisms. These last have an oblique extinction, give fairly bright colours with polarized light, and are probably kyanite; a few small grains of a plagioclase felspar can also be recognized. On closer study we perceive that in parts of the slide where the opacite and mica are less abundant, the interstitial material, on applying crossed nicols, exhibits—over spots of some size, perhaps $\frac{1}{15}$ inch wide—a uniformity of tint and of extinction, as though the opacite and mica, with some granular quartz,

were embedded in one irregularly defined grain of some mineral. Further examination shows that in one of the more definite instances this intervening material exhibits an oscillatory twinning, one set of bands extinguishing at $21\frac{1}{2}^{\circ}$, the other at $27\frac{1}{2}^{\circ}$ with the combination-plane, which indicates one of the more basic felspars.

Two hypotheses may be advanced in explanation of this structure. One, the partial dissociation of an original felspar-grain into granular quartz and white mica, as described in some cases from near Sudbury (Canada) ¹; the other, the recombination of felspar granules in a mixture (due to crushing) of quartz, felspar, opacite, etc. The latter seems to me more probable, for the amount of white mica is much smaller than it should be on the former hypothesis, and in parts of the felspar which are most free from quartz a granular structure can be detected, sometimes by shadowy outlines, visible only in certain positions with crossed nicols, sometimes by the presence of opacite, as if in a pencil sketch of the structure the lines had been made with dots. The larger flakes of brown mica are both smaller in size and more irregular in outline than in the specimen already described, but here also, once or twice, the stratulae of opacite are carried through them unbroken.

The hornblende is the most noteworthy mineral in this specimen. The outline of the crystals, as we might expect, is very ragged, but the usual cleavage is sometimes distinct. The colour is olive-green, the polychroism fairly strong: for vibrations parallel with a, pale greenish straw-colour; with b, strong sap-green; c, indigo green. The mineral contains, like the St. Gothard actinolite, not infrequent granules of quartz; possibly also some of felspar. The stratulae of opacite pass through the crystals practically unaffected; *even the waves and sharp flexures are preserved*.² In one case (see fig. 2, p. 108) a crystal of hornblende full half an inch long³ has formed without in any way disturbing this structure; biotite is occasionally enclosed by, and not seldom fringes, these crystals of hornblende. On a closer examination of the biotite and its mode of occurrence, we notice that the flakes often border the hornblende, and lie within a line which seems to be its natural boundary as if they cut into the mineral: groups of them occasionally occupying deep bays, as they may be called, in the grain. The most simple explanation of this peculiar association is that portions of an original crystalline grain of hornblende have been replaced by biotite,⁴ just as small grains of the former mineral replace part of a large grain

¹ Quart. Journ. Geol. Soc. vol. xlv. (1888) p. 36.

² It would have been easy to find instances where the flexures are much more pronounced than in fig. 2, but in some other respects this crystal is more instructive.

³ It goes right across the slice and is broken off by the edges, which are defined by cleavage-foliation.

⁴ This, however, would imply the breaking up of some felspar, because even if the hornblende originally contained alumina, more must be added, and potash obtained (if not wholly, in great part) from such a mineral as orthoclase; silica would then be liberated, and lime must be removed. In some cases the last might be used to form epidote or saussurite, in some a carbonate, which might or might not pass away in solution.

of augite. But by this change the stratulæ of opacite, whether straight or bent, are not affected, except that possibly a little of the most minute dust disappears.

That this rock was originally sedimentary, but afterwards became crystalline, seems highly probable; that it was then crushed seems certain, and that afterwards these large crystals of hornblende, the flakes of mica (in some cases at their expense), and some imperfect grains of felspar were developed seems the most natural inference. If this be so, those molecules at any rate which have built up the hornblende must have travelled about the rock for some distance, because even if we suppose that an elongated crystal existed at an earlier stage, it would be more or less crushed down if a statical pressure acted in the direction of its length, and it would be 'dragged out' and more or less distributed in a transverse direction if affected by a shearing force,¹ so that in either case a considerable displacement of some of the molecules is necessary to bring the crystal back into a position at right angles to the cleavage-foliation.

The process of crystal-building described above has evidently left the structure of the rock practically undisturbed, and resembles some forms of pseudomorphism. Hence the direct agent was probably water. As an hypothesis—but nothing more—I will venture on the following sketch of the process. After the rock had been crushed up, much of the material thus produced (in the first case) corresponded in composition very nearly with biotite. Where this correspondence was most close, crystal-building began in the presence of water. A nucleus once formed, further constituents would be derived from the water itself, which, when the pressure was greater, would have dissolved the finer dust, and would still continue to act on some of the materials. Thus the crystal would continue to grow, developing the more easily because the matrix was so nearly of the right composition. This would explain the peculiar development of the biotite described above, in parts of which the border of the crystal can hardly be said to be defined, and the process of development seems to have failed rather than to have been arrested. Quiet growth is indicated even more strongly by the large actinolitic crystals in the second case. Here we may suppose that there was a slight excess of magnesia and a defect of alkali; so hornblende began to form instead of biotite, and continued to grow as before until the conditions became more favourable to the production of the latter mineral, probably owing to the water becoming more alkaline, when it was at last even able to attack some of the hornblende already formed. Rocks very often illustrate the old proverb, 'robbing Peter to pay Paul.'

I have described these two rocks at considerable length because, so far as my experience goes, molecular movements on so large a scale are very exceptional after crushing or shearing. My collection contains over three hundred slides of Alpine rocks, and perhaps a

¹ We hear just at present so much about 'shearing' that one fancies some geologists suppose rocks to be sheep. Nature also subjects them to a treatment like that of a Bramah-press. This probably is the usual result of simple folding; while shearing results from overthrusting.

couple of hundred more from Scotland and other 'disturbed' regions, the majority of which bear marks of pressure, often considerable, sometimes extreme; but most of them testify strongly against any subsequent molecular movement of importance¹; a few only give some hint of it, and these two specimens are the first in which the evidence seemed to be conclusive.²

But when did these changes occur? Do the crushing and reconstruction both date from Tertiary times: are both connected with the rise of the present Alps? Upon their rocks, no doubt, the record of that grand process of mountain-making is writ in letters bold; but may not this be even as a palimpsest, on which full often the earlier characters can still be traced, nay, may remain sometimes almost untouched by the later scribe? Mountains there were on the site of the Alps at the beginning of Mesozoic, even in Palæozoic ages. The fragments in the Triassic rauchwacke, the fragments in the Carboniferous conglomerates alike exhibit, in their cleavage-foliation, a record of earth-movements by which their parent rocks had been already modified. The former at any rate supply materials for comparison.³ In the rauchwacke of the Val Piora, the Val Canaria, the southern opening of the St. Gothard tunnel, and on the flanks of the Nufenenstock, we find, among other rocks, fragments of a rather peculiar mica-schist (consisting, according to Dr. Grubenmann, chiefly of meroxene and margarite⁴), which also occurs *in situ* close at hand. The specimens from the two sources only differ in this respect, that those from the parent rock show more signs of crushing; they have been once oftener than the others 'through the mill.'⁵ It is therefore not improbable that these more important changes are pre-Triassic, even pre-Carboniferous. But, it may be asked, would not the Tertiary earth-movements have again crushed or sheared the rock-masses and so distorted or

¹ Contact-metamorphism is not considered as a cause, though of course it is very favourable to mineral change, because there is nothing in the structure of the rock to suggest it, nor can we connect the change with the possible intrusion of some granitic rocks at no very great distance from one of these localities. Also I do not reckon certain hydrous minerals, or such as calcite, which form readily.

² The actinolite-schists from the southern side of the St. Gothard Pass afford the nearest parallels to the rocks now described. The actinolites are irregular in outline, implicate quartz, etc., like that in the groundmass (so also sometimes does the biotite), and are not seldom associated with small flakes of the last mineral, much as described above, as if the biotite either had formed at the expense of the hornblende, or had been compelled, in a simultaneous crystallization, to acknowledge its suzerainty. The garnets also are often cleaved, sometimes broken, occasionally crushed; but the relation of the crystal-building to the mechanical disturbances is not so clear. At the St. Gothard, however, the evidence of the garnets suggests that the amount of shearing has been slight, so the actinolites might represent older crystals, not very different in position.

³ As it happens, the Carboniferous conglomerates, where I have examined them, have lain among gneisses and schists of a different type from those of the group described in this paper.

⁴ The *Disthen-Schiefer* of von Fritsch. The rock is noticed in Quart. Journ. Geol. Soc. vol. xlv. (1890) pp. 226-228, where Dr. Grubenmann's exhaustive investigation is quoted.

⁵ The enclosed fragments would be saved by the soft friable rauchwacke from suffering much. Their shapes and the position of their structure-planes, lying at all angles in a block of rauchwacke, show that they did not become foliated after being detached from the parent rock.

destroyed larger crystals of earlier date? In many cases undoubtedly they have done so; still, as already said, there is, I think, good evidence that many of the larger mineral constituents in the Alpine schists are of very ancient date and have passed through the Tertiary 'mill' with but little injury. In this, as in every mountain-region, zones of nearly uninjured rocks will be found to alternate with zones where they have been shattered almost beyond recognition.¹ It is accordingly possible that these more important changes must be carried back even to a very remote geological epoch.

To prevent misunderstanding, I wish to add that nothing in this paper is intended as an expression of doubt as to the possibility of such mineral reconstructions as have been described by Prof. Judd² and others. I fully believe that not only these have occurred, but also the evidence suggests that pressure has been a chief agent in producing the result. I think, however, that due caution is not always exercised in speculating on the 'flow of solid rocks under pressure.' Experiments, such as those of Spring, valuable and suggestive as they are, do not help us quite so far as is sometimes supposed, for the substances employed were homogeneous, while the crystalline rocks (with which geologists are really concerned) are heterogeneous. These substances also were opaque metals, so that the exact nature of the molecular changes could not be studied under the microscope. Hence it does not follow that if a piece of iron, for example, can be made to 'flow' under pressure, a piece of granite will do the same. The strength of a chain is that of its weakest link, so that, as it seems to me, before such a rock 'flowed' by gradual mineral reconstitution, without visible fracture, one of its constituents would have given way, and the 'flowing' would be that of a powdered mass. We have at present, so far as I know, no evidence to show that foliation, in a heterogeneous mass already crystalline, is produced without previous fracture.

In other words, I believe that mineral changes are due to more causes than one. Thus pressures equal in every direction are likely to produce such reconstitutions as the replacement of labradorite by scapolite, of felspar by a mosaic of quartz and white mica, of augite by granular hornblende; but pressure definite in direction, as it seems to me, will lead to crushing or shearing, and so to a foliated structure.³ The presence of water will undoubtedly facilitate change,

¹ Often this is so conspicuous that, until the right key was found, it was interpreted (very naturally) as an interstratification of granitoid gneiss and fissile mica-schist, or a transition from schist through gneiss to granite.

² Min. Mag. vol. viii. (1889) p. 186; Quart. Journ. Geol. Soc. vol. xlv. (1889) p. 175; Journ. Chem. Soc. vol. lvii. (1890) p. 404. The second paper contains a number of valuable references to the writings of other workers.

³ My remarks are restricted to rocks already crystalline. It may be worth mentioning that basic crystalline rocks, after crushing, recrystallize more readily than the acid, and the latter than sediments derived from them. In the Alps one may find in the same fold a hornblendic schist, in which mineral reconstitution has obliterated the direct evidence of pressure, a gneissoid rock where this still remains among partially reconstituted minerals, and a detrital rock in which only micromineralogical change has occurred, of which the origin is obvious.

perhaps is essential to it; so also will a high temperature: possibly, when the resulting structure is coarse, it too is no less essential. Altered crystalline rocks, especially crystalline schists, have been produced, unless I err greatly, in more than one way. Nature, in the ages of the past, has worked 'at sundry times and in divers manners.' These perchance we may succeed in distinguishing by means of the careful study of exceptional cases, especially where something is known as to the origin of the rocks.

DISCUSSION.

The PRESIDENT believed that there was every chance of the rocks being twisted in and out as stated; but there was no *a priori* improbability in the occurrence of either garnet or staurolite in Jurassic rocks, or in rocks of any age, provided the necessary materials were there and the conditions suitable.

Mr. ECCLES remarked upon the occurrence of two series of hornblendic intrusive rocks in the black-mica schists and gneisses of the Binn district. One series—the older one—is generally interbedded with the surrounding crystalline rocks, and has been subjected to the same pressure-modifications as the latter. The dykes of the other series cut across the foliation-planes of the gneiss and schist, and show no appreciable cleavage. No instance of any dyke had been observed in the schists and Jurassic beds of the Nufenen district by Prof. Bonney or the speaker.

Rev. EDWIN HILL, on the third paper, asked if there were any analogy in the crystals which do not disturb fossils, in some fossiliferous rocks—*e. g.* the Schistes d'Angers at Ste. Brigitte, in Brittany.

Mr. RUTLEY referred to a case in which the schistose banding of a rock had been seen to pass without interruption through crystals of staurolite.

Mr. TEALL also spoke.

The AUTHOR said, in reply to the President, that what might be theoretically possible he would not venture to affirm, but that, as a matter of fact, no Jurassic rocks in the Alps had authigenous garnets and staurolites, and all rocks with these minerals could be proved to be far earlier than any Mesozoic strata: to Mr. Eccles, that the gneiss near the Hohsandhorn might prove to be a very important rock in relation to the geology of the district. As regards dykes in Mesozoic rocks, he had never seen any, so far as he could remember, in the Central or Western Alps. With reference to Mr. Hill's remarks, he pointed out certain differences between the case of contact-formed minerals and those described in the third paper.