11. *On the* GROWTH *of* CRYSTALS *in* IGNEOUS ROCKS *after their* CONSOLIDATION. By Professor JOHN W. JUDD, F.R.S., F.G.S. (Read January 9, 1889.)

[PLATE VII.]

CONTENTS.

1. INTRODUCTION. SECONDARY ORIGIN OF THE "GRANOPHYRIC" STRUCTURES.

THREE years ago, in describing some basic igneous rocks from Scotland and Ireland, I expressed my conviction that a part, at least, of the structures known as *micropegmatitic* and *granophyric* were really of secondary origin*. At the same time, I stated that these structures were so much more clearly illustrated by the intermediate and acid rocks of the same district that it would be well to defer the discussion of the subject till my examination and description of the rocks in question should be completed.

The study of the intermediate and acid lavas (which, in 1874, I grouped under the old English field-name of "felstones") and of their plutonic representatives has occupied much of my time and thought during the last fifteen years. But so numerous and interesting are the problems connected with the wonderful metamorphoses which the minerals of these rocks have undergone, and so singular are the changes which have taken place in the structures of these rocks, that, in spite of a number of visits to the district and much labour in the laboratory, some time must yet elapse before the examination of the chief types and the elucidation of their mode of origin is completed.

In the meanwhile, however, certain discussions which have taken place concerning rock-structures and their significance—especially as a basis of rock-nomenclature and classification—render it desirable that the very definite and unmistakable evidence which I have ob-

* Quart. Journ. Geol. Soc. vol xlii. (1886), pp. 72, 73, pl. vii. fig. 8.

tained concerning the secondary origin of the characteristic structures of the "granophyric" rocks should be placed on record.

The examination of the field-relations of the remarkably varied types of acid and intermediate rocks which occur in the Western Isles of Scotland and the North of Ireland shows that rocks exhibiting the structures known as "granophyric" occur under certain well-marked conditions. The larger, truly granitic eruptive masses usually pass towards their peripheral portions into "granophyres"*; the smaller eruptive bosses and lenticular sheets ("laccolites") of the same rocks exhibit the granophyric character throughout; while the apophyses, and even dykes, proceeding from intrusive masses very often display these same structures, which are, in such cases, not unfrequently developed on a very minute scale. The structures which especially distinguish these *granophyric* rocks are the *micropegmatitic*, the *centric* or *ocellar* structure, the *pseudospherulitic*, the *microgranitic*, and the *drusy* or *miarolitic* structures.

I hope from the study of the remarkably fresh examples of Tertiary rocks, which are in texture intermediate between the granitic and the volcanic types, to illustrate the mode of origin of these various structures, and to show their relations one to another†.

2. Enlargements of detrital fragments of Crystals:—Quartz, Felspar, Hornblende, and Mica.

At the outset of this inquiry I must recall the important and suggestive discovery made by Mr. Sorby, and announced to the Society in his Presidential Address in 1880‡. Mr. Sorby showed that the so-called "crystalline sands" were produced by secondary growths of quartz upon the fragments of quartz-crystals that constitute sand-grains.

Like so many other of this author's discoveries, the new facts then announced have proved wonderfully suggestive and fruitful in new departures of thought.

Mr. A. A Young§, the late Dr. Roland D. Irving||, Mr. Van Hise¶, and other authors in the United States have shown how the structures of sandstones and quartzites may be explained by the application of principles discovered by Mr. Sorby; while Professor

* Throughout this paper I use this term not in the original sense in which it was employed by its author, Vogelsang, but with the meaning which Rosenbusch has proposed to attach to it.

† I may mention, in passing, that the study of the processes of crystallization by which the amorphous silica, replacing the calcic carbonate of chalk-mud, passes into the different varieties of hypocrystalline flint, throws much light upon the changes which have taken place in the ground-mass of igneous rocks. The problem is in this case simplified by the fact that there is only one mineral species involved in the change, namely, quartz; while in the devitrification of the glasses of igneous rocks there is much greater complexity.

‡ Quart. Journ. Geol. Soc. vol. xxxvi. (1880).

§ Am. Journ. Sci. 3rd ser. vol. xxiii. (1881), p. 257, and vol. xxiv. (1881), p. 47.

|| *Ibid.* 3rd ser. vol. xxv. (1883), p. 401.

¶ Bull. U. S. Geol. Survey, no. 8.

Bonney *, the late Mr. J. A. Phillips †, and others in this country have added largely to our knowledge of these interestiug processes. To Mr. Van Hise we are indebted for the further very important discovery that not only portions of quartz-crystals, but fragments derived from felspar-‡ and hornblende- § individuals, when exposed to favourable conditions, undergo, in the like manner, secondary enlargement; while Professor Bonney has shown that similar enlargements of biotite-fragments often take place during a development of foliation in argillaceous rocks ‖.

3. Enlargement of Crystals in Igneous Rocks.

That the crystals of many eruptive rocks are surrounded by irregular outgrowths, which are in crystallographic continuity with them, and appear to have been formed subsequently to the crystals themselves, has been recognized by many authors, such as C. Höpfner in 1881 ¶; Prof. G. H. Williams in 1882 **; F. Becke ††, K. Bleibtreu ‡‡, and E. Hussak in 1883 §§; by Dölter and Hussak in 1884 ‖‖; and by Dr. Max Koch in 1887 ¶¶. These authors, however, appear to have generally regarded the secondary outgrowths to the felspar or other crystals as having been formed while the rock was still in a molten state.

In a very valuable and suggestive memoir, to which I shall more particularly refer in the sequel, Dr. Erasmus Haworth, after describing some very remarkable examples of these outgrowths in the felspars of granitic rocks from Missouri, and discussing all the possible explanations of them, decided in favour of their having been produced *before* the complete consolidation of the mass in which the crystals occur ***.

The first petrographer who seems to have suspected that such outgrowths might have occurred *after* the consolidation of the rock was Dr. F. Becke; and this view is indicated in his very remarkable and thoughtful memoir on the "Eruptivgesteine aus der Gneissformation des niederösterreichische Waldviertels" †††. He appears to have seen that certain secondary growths in hornblende-crystals must have gone on when the rock was in a solid state. In 1887 Mr. Van Hise announced that he had found similar secondary out-

* Quart. Journ. Geol. Soc. vol. xxxv. (1879), p. 666, and subsequent memoirs.
† *Ibid.* vol. xxxvii. 1881, p. 6.
‡ Am. Journ. Sci. 3rd ser. vol. xxvii. (1884), p. 399.
§ Am. Journ. Sci. 3rd ser. vol. xxx. (1885), p. 231.
‖ Quart. Journ. Geol. Soc. vol. xliv. (1888), p. 15.
¶ Neues Jahrb. für Min. &c. 1881, Band ii. p. 180.
** *Ibid.* Beilage-Band ii. pp. 605–607.
†† Min. und petr. Mitth. vol. v. p. 147, &c.
‡‡ Zeitschr. d. d. geol. Ges. vol. xxxv. 1883, p. 489.
§§ Sitzungsb. der k. k. Akad. Wiss. Wien (1883), i. Abth.
‖‖ Neues Jahrb. für Min. &c. (1884), Band i. pp. 18–44.
¶¶ Jahrb. der. k. preuss. geol. Landesanstalt (1887), pp. 77–78 & 98.
*** The Archæan Geology of Missouri (Minneapolis, Minn. 1888), pp. 16–17. This paper also appeared in the American Geologist for May and June 1888.
††† Min. und petr. Mitth. vol. v. (1883), pp. 158, 159, 171, &c.

growths around crystals of both hornblende and augite in certain massive rocks from Michigan and Wisconsin *. In the following year Mr. G. P. Merrill described "Secondary Enlargements of Augites in a Peridotite from Little Deer Isle, Maine," and, like Mr. Van Hise, distinctly asserts that such enlargements must have occurred subsequently to the consolidation of the rock †.

The bearing of Dr. J. Lehmann's important researches on "Contractionsrisse in Krystallen" ‡ upon this question will be discussed in a later page of this paper.

4. Proofs that Growth of Porphyritic Felspars may take place after the consolidation and the alteration by weathering of an Igneous Rock.

In my studies of the Tertiary granophyric rocks of the Western Isles of Scotland and the North of Ireland, I have found abundant evidence that the growth of crystals of felspar and quartz goes on, at the expense of a more or less vitreous matrix, long after the solidification of the rock, and that in this fact we have a satisfactory explanation of the mode of origin of the several "granophyric" structures. I think that it will be desirable at the outset to describe a case in which the evidence of this action appears to me to be so clear as to place it altogether beyond question.

The rock in which the illustration occurs is one belonging to a group that, as I shall hereafter show, is very frequently represented among the lavas of the district; in chemical composition it lies on the borders of the intermediate and basic groups, and would be designated by French petrographers a "Labradorite;" in fact, it corresponds very closely indeed with the Icelandic labradorites so well described by M. Réné Bréon §.

As it is manifestly inconvenient, however, to employ the same term both for a rock and for a mineral, I would suggest that the rocks in question should be called "labradorite-andesites." They consist of large crystals of a lime-soda felspar, closely corresponding to labradorite (or sometimes to a felspar intermediate between that species and anorthite), scattered through a glassy base containing microlites of felspar, augite, and magnetite; olivine is usually so rare in the rock that we can regard it only as an accessory constituent. I shall show that, as the result of certain alterations, this Tertiary rock assumes the characters which are universally accepted as distinguishing the "labradorite-porphyrites," of which the well-known verde-antique and Lambay-Island porphyries are such excellent examples. In Iceland, however, these rocks are found in

* Am. Journ. Sci. 3rd ser. vol. xxxiii. (1887), p. 385.

† *Ibid.* vol. xxxv. (1888), p. 488–496.

‡ Zeitschr. f. Kryst. Bd. xi. (1886), pp. 608–612.

§ Notes pour servir à l'étude de la Géologie de l'Islande et des Iles Færœ (1884). I am greatly indebted to M. Bréon for supplying me with an interesting series of these rocks for comparison with those which I am studying in our own country.

a perfectly fresh condition, while in Mull and other parts of the Western Isles they may be traced undergoing certain changes due to both deep-seated and surface-action, and also exhibiting interesting examples of the so-called *propylitic* modification.

It is in a labradorite-andesite from Dun da Ghaoithe (Dun-da-gu) in Mull, a locality where rocks of this type are admirably displayed, that the enlarged crystals which I propose to describe occur. The principal minerals in the rock are large, idiomorphic felspar-crystals (which are shown by their extinctions, their specific gravity, and their flame-reactions to approximate to labradorite), and there are also a few individuals of augite and magnetite. Between these crystals, glass is frequently caught up, sometimes in angular portions, giving rise to the appearance called by Professor Rosenbusch "intersertal structure." The glassy matrix, in many places, is seen to have undergone much change, while the crystals are comparatively fresh and unaltered.

On close examination, the felspar-crystals in the rock-sections are found to exhibit remarkably irregular and ragged outlines; and a minute scrutiny reveals the fact that each crystal has a central core, which shows the rounded and sometimes corroded forms so frequently seen in the porphyritic crystals of rocks. When viewed between crossed nicols, the distinction between the central core and the irregular fringe surrounding it becomes very striking.

Looked at very carefully, the portion lying in the centre of each crystal is seen not only to exhibit corroded surfaces and glass-enclosures, but to be traversed by cracks, to contain bands of secondary inclusions, and to present planes of decomposition (kaolinization) which do not exist in the outer clear and transparent fringe In most cases the outer fringe is quite subordinate to the mass of the crystals (see Pl. VII. figs. 1, 2); but in a few instances the outer fresh portion is equal in area, as seen in thin sections, to the altered and more or less rounded core which it encloses (see Pl. VII. fig. 3). Occasionally the enveloped crystal can be seen to have undergone actual fracture; and in these cases, the cracks in the fractured crystals are found to be filled up, and the portions of the crystal to be cemented together by felspar-material, which extinguishes with the surrounding mass and not with the central core itself (see Pl. VII. fig. 2). It is a very significant circumstance that the crystals have only undergone enlargement where they are in contact with the glassy matrix, and that where other crystals lie against them, all growth has been prevented.

5. Changes in the Composition of the Outer Zones of Felspar-crystals during their Growth.

When studied by polarized light, these felspar-crystals exhibit one very important difference from similarly enlarged quartz-crystals. The crystallographic continuity of the inner and outer portions of the crystals is shown by the way the twin-planes sometimes pass from the one to the other (see Pl. VII. fig. 2); but the inner and outer portions of the crystal *do not extinguish simultaneously* when the section is rotated between crossed nicols. On the contrary, in rotating the crystal, after the position of extinction of the internal core has been passed, a dark zone of extinction makes its appearance around the central mass, and, as rotation goes on, this dark zone passes slowly and gradually outwards through the surrounding fringe (see Pl. VII. fig. 3).

Nothing can be more striking and suggestive than this beautiful phenomenon, which it is possible to observe and verify in the case of many of the crystals in this very interesting rock.

I think there cannot be any real doubt as to the true explanation of the remarkable appearances which I have been describing.

The more or less decomposed character of the glassy ground-mass in these rocks, as compared with the crystallized minerals, shows that the vitreous part is in a less stable condition than the crystalline. That long after the consolidation of the rock the crystals grew outwards irregularly, at the expense of the surrounding glassy magma, is clear; this being shown by the fact that where two crystal faces are in juxtaposition without the intervention of glassy material, no exterior fringe is formed. The phenomenon which these particular crystals exhibit—and which it is especially important to bear in mind—is that they have not only been developed before the secondary outgrowths have been formed around them, but that they have suffered a considerable amount of injury and alteration from the action of mechanical and chemical forces. This is especially well shown when the junctions of the old and the new portions of the crystal are studied with high microscopic powers.

On the other hand, it can be proved in the same way that the period since the development of the outer fringe of new material has been sufficient for the formation of new cracks and bands of enclosures, which traverse both the old and new portions of the crystals alike. In most cases the twin-lamellæ pass from one portion to the other; but whether this twinning was developed before or after the outgrowths were formed can only be proved in the cases (which sometimes occur) when incipient kaolinization has taken place along the twin-planes, which are thus shown to have been solution-planes, before the outward growth took place (see Pl. VII. fig. 1).

In a few instances, I have found proof that secondary twinning has been developed in the fringe of new material, but does not extend into the old nucleus.

The remarkable behaviour of the zone of extinction is well worthy of study and consideration. The existence of zoned plagioclastic felspars with areas giving different extinction is well known; and in most of these the more basic portions form the centre and approximate to the Anorthite-extreme, while the outer zones are successively more acid in character and approach towards the Albite-limit. But, in nearly all such cases the successive zones are clearly and sharply marked off from one another, and they not unfrequently exhibit numerous solid and liquid inclusions, or other indications that the growth of the crystal had been arrested at successive stages, and that, after an interval, growth had been resumed under somewhat different conditions. In the felspars I am now describing, however, the zone of extinction passes gradually, and *without any kind of break whatever*, from the original central core through the secondary peripheral fringe. Taking note of the amount of rotation required to produce extinction in different zones in the cases of crystals exhibiting the largest periphery, I have found it to be such as to lead me to conclude that some crystals with a composition between labradorite and anorthite have an irregular fringe which, as we pass outwards, corresponds to every intermediate stage through the Andesine and Oligoclase series, and sometimes approaches, if it does not actually reach, the Albite-limit *.

Nowhere, I think, could we have a more convincing illustration of the truth of Tschermak's beautiful theory of the felspars. We find absolute evidence of the *perfectly gradual change* of the optical characters of these crystals as we follow them from the original central mass through the portions representing consecutive additions to it.

Nor is the explanation of the facts observed difficult. When the rock, by cooling, assumed the solid state, the stable well-formed porphyritic crystals were separated by portions of vitreous material, this vitreous material consisting of unstable mixtures of various silicates of lime and the alkalies.

We must never forget that in the deep-seated rocks—and it is in such only that these and similar changes seem to occur—the whole mass, crystals and base alike, must be permeated by liquids and gases; and chemical reactions (like those involved in the process of schillerization) can readily take place.

The tendency of the more basic minerals to separate from a magma before the more acid ones, which has been so clearly pointed out by Rosenbusch and other authors, leads to the gradual exhaustion of the lime; and as the proportion of this ingredient in the limited portion of magma that can be drawn upon is diminished, more and more of the alkaline constituent must be taken up by the growing felspar, which thus gradually passes from a basic lime-felspar towards an acid alkali-felspar. At last little else than the silica may be left, and, as we shall see hereafter, this tends to crystallize as quartz, sometimes simultaneously with, and sometimes after the whole of the felspar has crystallized.

Prof. Lagorio, in a very useful and painstaking investigation, has endeavoured to apply the important results obtained by the late Dr. Guthrie on "Eutectic Compounds" to the explanation of the

* M. Michel-Lévy is of opinion that the same phenomenon would result if the different zones of the felspars, instead of consisting of homogeneous materials of different chemical compositions, were variously built up of "submicroscopical" (*i. e.* ultramicroscopical) twin-lamellæ arranged on the pericline and albite types. For the purpose of my argument it is not of great importance which theoretical view of the molecular structure of the felspars is accepted. It is sufficient to have demonstrated that in these cases the angle of extinction varies gradually and progressively as the crystal grows at the expense of the residual glass.

nature of the glassy base which is found in igneous rocks *. An admirable discussion of Lagorio's results has been given by Mr. Teall †, who has supplied further illustrations of the subject. The interesting analyses of Lagorio show very clearly that the glassy magmas of igneous rocks are just of such a composition as to permit anges of the kind I have been describing to take place in them.

6. The peculiar Conditions which have given rise to the Phenomena observed in the particular case now described.

It may not unreasonably be asked why the felspars in this particular rock should exhibit this phenomenon in such a very marked and unmistakable manner; and it may fairly be objected to the views I have expressed that, if the phenomenon of crystal-growth be a common one, it ought to be more frequently and easily traced. To this objection I think that I am able to give a complete reply.

Careful study of a large number of cases convinces me that this growth of felspar-crystals at the expense of the surrounding unstable magma is of very frequent occurrence in rocks which have been deep-seated at any part of their history. A very interesting series of rocks which I have received from New South Wales by the kindness of my friend T. Edgeworth David, F.G.S., shows that the secondary growth of a felspar may even take place after the advanced kaolinization of the original crystal.

But in the great majority of cases, these secondary outgrowths are undoubtedly formed while the original crystal is still fresh and unaltered, and thus it is not easy to demonstrate that the growth has gone on after the surrounding magma has become solid.

The clearness of the evidence in the particular case described is the result of the circumstance of the *alteration of the felspar* before its growth recommenced; and of this peculiarity I am able to give a very simple explanation. The labradorite-andesite in which these crystals occur is one of the old series of "felstone"-lavas which I described in 1874 as belonging to the earliest period of eruption in the Mull volcano. The lava-stream had been exposed to denudation and weathering action for long periods of time, sufficient to allow of the mechanical injury and partial kaolinization of the felspar.

Subsequently, this old lava was buried to the depth of several thousands of feet by the later out-welling of basaltic and other lavas—the consequence being that the mass was placed under just the conditions which are favourable to the renewed growth of the felspar-crystals. In the presence of these conditions—pressure, heat, and the free passage of liquids and gases through the solid rock-mass—the crystals already corroded by their surrounding magma, and altered by surface-agencies, renewed their youth and recommenced their growth. But, depending, as they did, for the supply of fresh material on the limited volumes of glass surrounding them, the remarkable change in composition, as the lime was extracted from the glass faster than the soda, was brought about.

* Min. u. petr. Mitth. viii. (1887), p. 421.
† 'British Petrography' (1888), pp. 391–401.

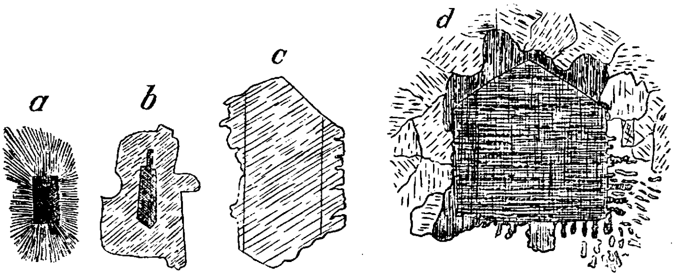
7. Relation of these facts to Dr. Lehmann's theory of the Origin of Perthite-structure, and other recent researches.

There are some recent researches that give very considerable support to the views I have been advocating. Prof. Lehmann has shown that, on heating and cooling, crystals undergo contraction along planes which he calls "Contractionsrisse." These "Contractionsrisse" he shows are sometimes planes of cleavage and at other times gliding-planes. He refers the beautiful structure known as perthite and microperthite—so commonly seen in micorocline—to the separation of the orthoclase-crystals along their "Contractionsrisse," and the deposition of secondary albite in the fissures thus formed.

In this case we have an example of an action strikingly similar to that which I have been describing*.

Dr. Erasmus Haworth, in the very interesting communication to which I have already referred, gives descriptions and drawings of a striking series of appearances which he detected in certain Missouri granites. He shows that idiomorphic crystals of felspar sometimes exhibit enlargements similar to those I have been describing (figs. *b* and *c*) and at other times a pseudo-spherulitic fringe (fig. *a*).

Orthoclase-Crystals from Granite of Missouri.
(After Dr. E. Haworth.)



In *a* the crystal is surrounded by a pseudo-spherulitic border; in *b* and *c* there are enlargements with continuous cleavage; and in *d* "the idiomorphic orthoclase is partly surrounded by a secondary growth, and partly by a micropegmatite in which the felspar is attached to the original crystal and oriented with it."

Still more remarkable are the cases which he cites of idiomorphic orthoclase, surrounded by secondary outgrowths, which in parts exhibit all the characters of a true micropegmatite, the central

* "Ueber die Mikroklin- und Perthit-Structur der Kalifeldspathe und deren Abhängigkeit von äusseren z. Th. mechanischen Einflüssen." Jahres-Bericht der schles. Gesellschaft für vaterländische Cultur, für 1885, Sitzung vom 11 Feb., also in same Journal, p. 92, and 1886, pp. 119–120. See also Zeitschr. f. Kryst. Bd. ii. 1886, pp. 608–612.

Dr. Lehmann informs me that he hopes soon to publish full details, with illustrations, of these very important researches.

crystal and the outgrowths extinguishing together (fig. *d*). Dr. Haworth's illustrations of these phenomena are so excellent that I prefer to reproduce them rather than to select from numerous similar cases that have come under my own observation. It is true that Dr. Haworth does not take the view that these secondary outgrowths were formed after the solidification of the mass, but rather that "in the process of cooling the felspar-crystals were formed and floated about in the magma for some time, as the porphyritic felspars do in the magma of a porphyry" *. After the proofs I have now given that such secondary growths can and do take place in a rock-mass, long after it has become solid, the objections raised by Dr. Haworth to this explanation disappear.

When it is remembered how crystals are developed in the midst of solid rock-masses, during contact-metamorphism, this growth of crystals in solid igneous rocks ought to occasion no surprise.

My friend Prof. G. H. Williams—in whose laboratory have been carried on so many researches having an important bearing on the questions discussed in this paper—has in his various memoirs and also in private correspondence called my attention to phenomena which seem at first sight to be inconsistent with the theory of schillerization which I have propounded. He refers to the case of felspar-crystals which contain a central mass filled with inclusions, but in which an outer zone is seen quite free from such inclusions.

I have studied many such cases, and in some of them have been able to prove that the clear outer zone is really a secondary outgrowth to the crystal. I have found what I think is indisputable evidence that the outer portion of a crystal may be removed under one set of conditions, and that under other conditions its growth has recommenced again; just as a crystal of alum would behave if first taken from a saturated solution and put into warm water, and then after a certain interval transferred again to the original or some other saturated solution of an alum.

I must postpone to a future occasion the discussion of the exact nature of the operations which result in the formation of the different varieties of micropegmatitic, centric, pseudospherulitic, and miarolitic structures, respectively. In all these cases, I believe, I shall be able to show that, in vitreous or imperfectly crystallized material, the instability which exists has permitted the formation in the solid rock of outgrowths to preexisting stable crystals.

I shall show that there is every gradation from a glassy groundmass to one characteristic of the so-called granophyric rocks, and prove that the characteristic structures of those rocks must be attributed to secondary rather than to primary devitrification. The cavities found in the "miarolitic" or drusy granites—which are so difficult to account for on any other hypothesis—will be shown to be fully explained by the contraction which a more or less glassy ground-mass has undergone during devitrification.

* *Loc. cit.* pp. 15–16.

8. Bearing of these considerations on the problem of the Origin of Foliation in the Metamorphic Rocks.

It is scarcely necessary to point out the important bearing of this principle of the growth of crystals—and especially of felspar-crystals—in solid rock-masses upon the great question of the origin of foliation in rocks, a question in the discussion of which the Fellows of this Society have taken so prominent a part.

That, as the result of contact-metamorphism, many well-defined mineral species are developed in the midst of solid rocks, the crystals growing at the expense of and deriving their materials from the surrounding detrital fragments, has long been recognized. These phenomena find many beautiful illustrations in the so-called "spotted schists." I hope to be able to show, on a future occasion, how large a part a similar action plays in producing the characteristic structures of many fresh and apparently unaltered igneous rocks.

The founders of the theory of dynamo-metamorphism—Scrope and Darwin—very clearly perceived that in the study of igneous rock-masses which have been subjected to movements and internal stresses, we find alike the clearest analogies and the simplest and most readily studied examples of the processes which go on during the production of foliation in rocks. Those who have done most towards establishing the theory on its present firm basis, by tracing with the aid of the microscope the *actual* changes which the minerals of rocks undergo while the development of foliation is in progress—and I especially refer to the beautiful researches of Lossen and Lehmann and those of students of petrography who, like Dr. Reusch in Scandinavia, Prof. Williams in America, and Mr. Teall in this country, have sought to follow in their steps—have skilfully and patiently pursued the same methods.

Charles Darwin was able to show, by the aid of a pocket-lens and blowpipe only, that in a holocrystalline lava in the Island of Ascension which had been subjected to powerful internal mechanical stresses, the felspar, augite, and magnetite had separated from the glassy mass in distinct and parallel folia *. He clearly perceived, what some in more recent years have quite failed to realize, that mechanical force *per se* is wholly incompetent to produce a true foliation in rocks; but that the mechanical force becomes really effective by determining and controlling the operations of chemical affinity and crystallization; and it is by these that the metamorphoses of the minerals in rocks are brought about which result in the development of the foliated structure.

The more carefully these metamorphoses of the minerals in rocks are studied, and the more clearly it is perceived that the whole structure of deep-seated rocks may undergo a complete transformation, during such metamorphoses of their constituent minerals, the less difficulty will be felt in accepting the teachings of Scrope and

* Darwin's 'Volcanic Islands,' published in 1844, p. 56 (p. 64 of reprint issued in 1876). I have studied Darwin's original specimens with the microscope, and can confirm the wonderful accuracy and acumen of his researches.

Darwin, which have in recent years received such valuable illustration from the admirable researches of Lossen, Lehmann, and many other petrographers.

EXPLANATION OF PLATE VII.

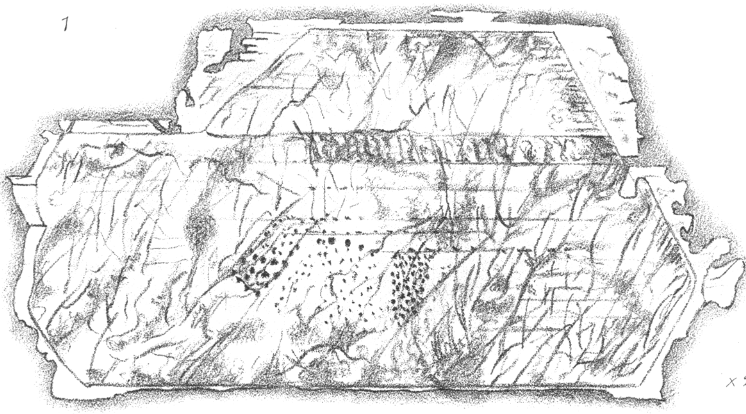
Outgrowths to felspar-crystals in labradorite-andesite, Dun da Ghaoithe, Isle of Mull.

Fig. 1. Crystal of felspar as seen, magnified 25 diameters, by ordinary light. The contrast between the original crystal with its numerous cracks (some of which show incipient kaolinization along their sides) and the comparatively fresh and irregular outgrowths of secondary origin is very clearly seen.

2. The same crystal as seen with crossed nicols. The difference of the extinction-angle between the central core and the surrounding secondary fringe causes the latter to remain light, while the former, except where traversed by twin-lamellæ, is dark. It is very noticeable that newly deposited felspar-substance filling the cracks of the original crystal extinguishes with the outer fringe.

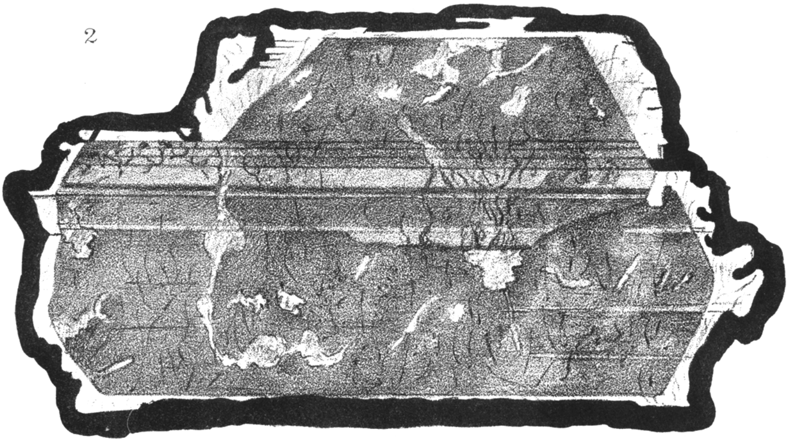
3. Another crystal of felspar as seen magnified 75 diameters. The great extent of the outgrowths, as compared with the original rounded grain of felspar, is very striking; as is also the very irregular development of the secondary fringe. The crystal is represented as seen with crossed nicols, the stage being rotated into such a position that the zone of extinction, traversing the portions of the crystal which have the same chemical composition, lies in the midst of the secondary outgrowth. As the stage is gradually rotated this zone of extinction is seen to pass slowly and progressively outwards, *without any kind of break*, till it reaches the most distant apophyses. Some of these last must have a composition very closely approximating to that of albite.

1



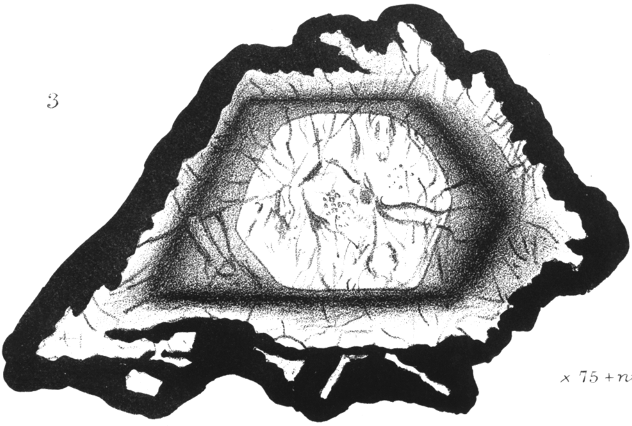
× 25

2



× 25 + nic.

3



× 75 + nic.

Parker & Coward, lith.

West, Newman & Co. imp.

SECONDARY OUTGROWTHS TO FELSPAR-CRYSTALS IN LABRADORITE-ANDESITE. I. OF MULL.