Chapter 27 Contact-metamorphism around the Galloway granites

The granites of the Galloway district have produced important alterations in the sediments into which they have been intruded. In his remarkable paper on "The Convolutions of Strata and their Meeting with Granite", Sir James Hall<ref>Trans. Roy, Soc. Edin. Vol. vii., p. 79.</ref> calls attention to these alterations. In speaking of the exposures on the west side of Loch Ken, where he traced the granite veins to their junction with the main mass, he says: "In the immediate neighbourhood of the granite, to the distance of a foot or two, and not more, the stratified matter has in many instances assumed a highly micaceous character so as to deserve the name of mica-slate, and perhaps gneiss". And again: "The quality of this stratified mass [the Silurian formations of the Southern Uplands of Scotland] from one side of the island to the other seems to be uniform throughout, except in the immediate neighbourhood or contact of the granite, where it assumes a micaceous character, approaching to the character of gneiss or mica-slate. This furnishes a most notable indication of the action of heat, since the granite, by its local intensity, has performed the very effect which Dr. Hutton ascribes to the general heat below, as acting upon the lower beds, and converting them into gneiss".

These two quotations prove that Sir James Hall not only recognised the metamorphic effect of the granite upon the adjacent sediments, but that he realised the importance of the facts in relation to the origin of extensive areas of gneiss and schist. The concluding sentence of the second quotation contains the germ of the theory, recently advocated by M. Michel Lévy in France, that the extent of the contact zone is dependent on the depth at which the intrusion took place. The exposures of granite are regarded in many cases as the apices of pyramids, which expand downwards, and regions of gneiss and schist are supposed to represent areas where denudation has been carried on to such an extent as to expose the lower portions of the "appareils granitiques". It will be shown in the sequel that the metamorphism of the sediments extends to much greater distance than was recognised by Sir James Hall.

A long time elapsed after the memorable observations by Sir James Hall before the phenomena of contact-metamorphism in the Galloway district again attracted the attention of geologists.

During the progress of the Geological Survey they were found to occur on a large scale round each of the three important masses, and an extensive series of specimens was collected. A general account of the metamorphism was given in the Memoirs explanatory of Sheets 9 (1877) and 4 (1878), and special attention was called to the crystallisation of the sediments and to the development of mica in the neighbourhood of the granites.

In recent years the two important communications already cited, have been published, containing descriptions of the microscopic characters of the metamorphic rocks, the one by Messrs. Allport and Bonney,<ref>Report on the Effects of Contact-Metamorphism exhibited by the Silurian Rocks near the Town of New Galloway. Proc. Roy. Soc. London. Vol. xlix. (1889), p. 79. </ref> and the other by Miss Gardinen<ref>Contact Alteration near New Galloway. Quart. Jour. Geol, Soc. Vol. xlvi. (1890), p. 569.</ref>. Both papers relate to the alteration surrounding the Cairnsraore of Fleet mass.

Messrs. Allport and Bonney especially describe the change which has been effected in sediments, varying from "silky clays to greywackes", along the west side of Loch Ken [NX 65185 73071]. They record the presence of quartz, brown mica, white mica, hornblende, augite, garnet (rare), epidote (not common), tourmaline (rare), and black opaque materials. They conclude that the biotite which is so extensively developed in argillaceous sediments must be an iron-mica, containing only a small percentage of magnesia. In describing the alteration of the greywackes, they call attention to the partial destruction of the typical clastic structures.

Only the ghost of such structures remains in the altered rocks. The original quartz grains are represented in the altered rocks by subangular individuals, which are larger than the constituents of the quartz-mica aggregates, and the original felspars have been replaced by chalcedonic or micro-crystalline quartz containing minute flakelets of white mica.

Miss Gardiner's paper deals especially with the altered rocks occurring in Knocknairling Burn [NX 62183 77101] and in the neighbourhood of Knocknairling Hill, to the west of the town of New Galloway. The progressive changes seen in beds of grit and shale as they are traced along the strike towards the granite are described. The grit is shown to pass into a coarsely crystalline gneissose rock, composed of quartz, two micas, garnet, and sillimanite, and to contain in the immediate neighbourhood of the granite lenticles of quartz and garnet. The garnet-sillimanite-mica■quartz rocks described and figured by Miss Gardiner must certainly be regarded as some of the most remarkable products of contact-metamorphism hitherto described. In the same paper it is proved that the shales are converted into schistose aggregates of quartz and two micas, with which opaque dusty matter and occasionally large crystals of chiastolite are associated.

We now proceed to give a general account of the metamorphism of the Galloway district, based on specimens in the Survey Collection. Most of these specimens have been collected from the contact zone surrounding the Loch Dee mass, but the specimens from other areas are sufficient to show that the different masses do not present any marked differences as regards the nature of the products formed. Where similar rocks have been acted upon to the same extent the resulting products are the same.

The rocks which have been metamorphosed comprise grits, greywackes, ordinary shales and slates, black shales highly charged with carbonaceous matter and pyrite, radiolarian chert, impure calcareous rocks, and the igneous rocks underlying the radiolarian cherts. A special feature of the Silurian rocks of the Southern Uplands is the great development of both coarse and fine-grained grits and greywackes of complex composition. Normal argillaceous sediments make up only a small portion of the area. It follows, as a necessary consequence of this fact, that the contact phenomena surrounding the Galloway granites must differ in a marked manner from those observed in the Skiddaw district, and in that portion of the Vosges which has been rendered classic by the remarkable memoir by Professor .Rosenbusch.<ref>Die Steiger Sehiefer mid ihre Contaetzone an den Granititen von Barr-Andlau und Hohwald. Straabourgh, 1877.</ref>

When a granite mass is intruded into sediments of uniform composition, as in the case described by Professor Rosenbusch, the metamorphic zone may be separated into subordinate zones characterised by special minerals or by special structures. The successive zones represent different grades of metamorphism in one and the same type of rock, and they are concentric with reference to the granitic mass. When, however, as in the case of the Galloway granites, the intrusion has taken place in a set of complex sediments of variable character, the separation of the metamorphic aureole into subordinate zones, continuous round the central mass, becomes impossible. Each member of the complex group possesses its own special type of metamorphism, and a sub-division of the metamorphic area into zones based on one type of rock is not applicable to the area as a whole.

Another point in which the metamorphism of the Galloway district differs from that of Skiddaw and Barr-Andlau is the comparative rarity of the aluminous orthosilicates. Andalusite and sillimanite occur, but never in such abundance as to form a striking feature of the metamorphic aureoles. This is doubtless due to the fact that pure argillaceous sediments are comparatively rare. The composition of the rocks in most cases admitted of the development of complex silicates, such as garnets and micas.

Before proceeding to give an account of the altered rocks, it will be desirable to offer some remarks on the minerals of which they are composed.

Biotite is unquestionably the most characteristic mineral. Its presence is one of the earliest indications of an approach to the granite, and it gives rise to the purplish brown tint which previous observers have referred to as especially characteristic of many of the altered rocks. In the earlier stages of alteration it occurs in irregular scales, and, as the metamorphism advances, the individuals increase in size. The usual colour is reddish brown, and the pleochroism is intense. The mineral is found in almost all the altered rocks, whatever their original character may have been. Thus it occurs in the grits, greywackes, slates, shales, igneous rocks, and even in the radiolarian cherts. The individuals are usually irregular in outline, and several often occur together. Sometimes the rocks have a spotted appearance, due to local aggregations of biotite.

M. Michel Lévy has especially directed attention to the contrast in the mode of occurrence of the biotite in igneous rocks and altered sediments. In the former it belongs, as a rule, to the earlier stages of consolidation, and consequently exhibits a considerable amount of idiomorphism; in the latter it is interfered with by quartz, and often acts as a kind of paste in which the other constituents are embedded. This feature is illustrated by the biotite of the rocks now under consideration, especially in those which do not exhibit the highest grades of metamorphism. The biotite of the contact rocks, like that of the igneous rocks, often shows pleochroic halos round minute inclusions.

White mica, though not so abundant as biotite, is frequently present. It is usually similar in form and size to the biotite. In some of the highly metamorphic rocks it occurs in large patches, showing micro-poikilitic structure in consequence of the presence of rounded inclusions of quartz (S2203) [NX 64 73], graphitic matter (S6602) [NX 62 76], and other substances.

Quartz. — In the grits, greywackes, and shales, silica is present either as grains or granular aggregates of quartz. In the cherts it occurs in the crypto-crystalline or chalcedonic condition. As the coarser forms of sediment are traced into the metamorphic zone the original outlines of the clastic grains become more or less obliterated. Even in highly altered rodks containing much biotite, indications of the original clastic structure may often be seen, owing to the presence of individual grains or aggregates of quartz, which are much larger than the constituents of the matrix. In all such cases there is, however, a want of definiteness about the boundaries. The peripheral portions of the quartz grains have been affected by the agencies which have recrystallised the matrix.

The change in the chalcedonic silica of the cherts is of special interest. The crypto-crystalline condition passes gradually into the micro-crystalline condition, and this again into a coarsely crystalline condition in which the individual grains measure one or two mm. in diameter. The large individuals in the coarse-grained quartz rocks, which represent the extreme phase of the alteration of the cherts, are very irregular in outline. The junctions of the contiguous grains are of the kind for which Professor Blake has proposed the term "sutural", because they remind one of the sutures which separate the different bones of the skull. It appears, therefore that in highly siliceous rocks, such as the cherts, adjacent individuals coalesce to form larger individuals under the influence of contact metamorphism.

Another mode of occurrence of quartz is seen in those rocks which contain minerals having a pronounced micro-poikilitic structure. In these cases the quartz forms minute isolated inclusions with rounded outlines in the containing mineral.

The main facts with regard to the mode of occurrence of quartz in the metamorphic rocks may thus be summarised. In the altered grits and greywackes it occurs as irregular grains and granular aggregates of considerable size in a matrix largely composed of small grains associated with biotite; in the intermediate phases of the alteration of the cherts, and in some other rocks, it forms a mico-crystalline mosaic; in the final stages of the alteration of the cherts it forms coarse-grained aggregates with sutural junctions; and in the micro-poikilitic minerals it occurs as minute rounded grains.

Felspar. —In many cases the felspar, which is abundant in the grits and greywackes of the original rocks, appears to have been altered in the manner described by Messrs. Allport and Bonney. The original grain appears to have been replaced by crypto-crystalline or micro-crystalline aggregates of a mineral which is presumably quartz and minute flakelets of a white mica. Bearing in mind the tendency which felspars have to a micaceous type of decomposition, it is, however, possible that this change may not be due to the effect of contact action upon fresh felspar, but rather upon felspar already attacked by the surface agencies. At anyrate water-clear felspar certainly occurs in many of the highly altered rocks in association with quartz and biotite. A good example of this mode of occurrence is furnished by a specimen taken from a point south of Craiglee Hill [NX 47099 96250], near the head of Loch Doon (S2549). The rock is fine-grained and of a dark purplish colour. It is essentially composed of the ubiquitous brown mica and a mosaic of quartz and felspar. A mineral somewhat doubtfully referred to andalusite, and a few grains of iron-ore, also occur. In this case, and in many others of a similar character, there is no reason to regard the felspar as due to impregnation by the granite magma. There are often cases, however, of a more doubtful character, and some in which an intimate intermixture of granite and sedimentary material has undoubtedly taken place. The latter occur on a small scale, and only in the immediate neighbourhood of the contact. A junction specimen from the north-west slope of Meikle Craigrarson [NX 48078 87199] (S4968) may be cited as an illustration. It consists of a medium-grained aplite in contact with the brown resinous quartz-rock which represents the extreme phase of alteration of radiolarian chert. When examined with a hand lens detached fragments and isolated grains of the characteristic quartz of the chert may be seen lying in the mass of aplite, and the material of the aplite can also be seen insinuating itself between the quartz grains in the altered chert. Under the microscope these phenomena are still more marked. In that portion of the slide which is mainly composed of altered chert somewhat cloudy orthoclase occurs, moulded on the larger quartz grains which represent the chert. In the other portion of the slide, which is mainly formed of aplite, detached grains and fragments of the altered chert may be recognised. The quartz of the altered chert and that of the aplite can easily be distinguished from each other under the microscope, in consequence of the minute inclusions of biotite which occur exclusively in the former. In this case there can be no doubt that the felspar of the altered rock has been derived from the granite magma.

In the case above referred to, the felspar is orthoclase, but in a few abnormal rocks from the immediate neighbourhood of granite masses plagioclase has also been observed. Its mode of occurrence is quite different from that of the orthoclase just described. Instead of occurring in interstitial patches it behaves rather as a porphyritic constituent. The individuals are often zoned and idiomorphic, and closely resemble the plagioclase of the granite rocks.

M. Michel Lévy has called special attention to the "felspathisation" of the rocks into which granite has been intruded, and he appears to regard the felspar in all cases as foreign to the rock into which the intrusion has taken place. The contact zones surrounding the Galloway granites certainly do not furnish illustrations of such felspathisation on any large scale In many cases the felspar has doubtless been formed out of the constituents of the original rock, and in the few in which it has been introduced the action has occurred only in the immediate neighbourhood of the granite.

Andalusite. —This mineral, including its variety chiastolite, is by no means characteristic of the contact zones. It has been observed only in a few localities. The fact is undoubtedly to be accounted for by the comparative rarity of the purer forms of argillaceous sediment. Miss Gardiner has recorded the occurrence of typical chiastolite in the altered shales of Knocknairling Hill. Here it sometimes forms a conspicuous feature on the weathered surfaces of the rocks and crystals measuring an inch or more in length may be obtained. The mineral also occurs in the altered black shales near the granite contact on Meikle Craigrarson [NX 47823 87247]. Here it forms long slender prisms, which are idiomorphic in the prismatic zone. Under the microscope they are seen to be often more or less replaced by aggregates of a white mica, and to contain inclusions of graphite. These inclusions are not abundant, and they are not aggregated in the central portions of the crystals, as is so commonly the case with the black inclusions in chiastolite. Typical chiastolite occurs in black shales containing graptolites, near Black Gairy [NX 42200 85296], Buchan Hill [NX 42734 81648], Glen o' Trool [NX 41838 80254], on the west side of the Loch Dee mass.

Sillimanite. —This mineral has been recorded by Miss Gardiner in the highly altered rocks of Knocknairling Hill. It occurs in long slender needles, which are sometimes aggregated in clots. As a rule the needles occnr as inclusions in the mica and quartz. The rocks of Knocknairling Hill show a higher grade of metamorphism than that observed in any other district, and up to the present this is the only locality in which sillimanite has been recorded.

Garnet. — Red garnets, which are, however, almost colourless in thin sections, are extremely common both in the altered shales and grits. In fact, next to biotite, garnet is the most characteristic contact mineral in the rocks surrounding the Loch Dee and Cairnsmore of Fleet masses. It occurs in grains and idiomorphic crystals of the usual form. The individuals increase in size as the junction is approached. The largest are to be found in the highly altered grits of Knocknairling Hill, in which sillimanite occurs. The central portions are usually crowded with inclusions of a colourless substance, possibly quartz, of irregular form but usually with more or less rounded contours. Occasionally mica flakes and needles of sillimanite also occur as inclusions in the garnet.

Garnet is by no means limited to the immediate neighbourhood of the granite. It is one of the first minerals to form. In tracing the chert-shale series from the unmetamorphosed area towards the granite the shaly streaks and partings are seen to become crowded with small garnets before any notable change has taken place in the chert. Garnets may be seen in the altered shale and radiolaria in the chert of the same slide. A good example of this is furnished by a specimen from Polmaddy Burn [NX 50035 87583], five miles W.S.W. of Carsphairn (S4956).

Graphite. — The unaltered rocks belonging to the chert-shale series are often highly charged with carbonaceous matter in the form of fine dust. In the neighbourhood of the granite masses this is converted into crystalline aggregates and plates of graphite, giving brilliant reflections when viewed under suitable conditions. The graphite may be easily isolated by treating the powder of the rock with cold hydrofluoric acid for some days, and then washing the residue. The comparatively light graphite is readily separated from the heavier undecomposed particles. It occurs for the most part in irregular crystalline aggregates, measuring on the average about 0.03mm. in diameter; but extremely thin plates are by no means uncommon. These show brilliant metallic lustre in ordinary reflected light or when viewed with a lieberkuhn, and hexagonal outlines, though rare, may occasionally be seen. In a specimen (S4969) from Meikle Craigrarson [NX 47823 87247], which illustrates this mode of occurrence of graphite in great perfection, quartz and graphite are the two principal constituents, but thin layers containing long slender prisms of chiastolite also occur. White mica is present in small quantity, and minute crystals of tourmaline and rutile have also been recognised. The quartz forms a somewhat coarse micro-crystalline aggregate. The individuals are polygonal in outline, and generally contain numerous minute opaque inclusions, probably also graphite, in their central parts.

It is tolerably certain that the original rock was a carbonaceous chert containing thin partings of shale. In the process of metamorphism the original minute particles of carbonaceous matter coalesced so as to form crystals and crystalline groups of graphite; the molecules of silica in the chert also coalesced to form the crystalline aggregate of quartz, and the argillaceous particles of the shale furnished the material for the crystals of chiastolite.

A similar development of graphite has been described by Beck and Luzi<ref>Ueber die Bildung von Graphit bei der Contactmetamorphose. Neues Jahr. (1891). Vol. ii., p. 28. See also Erlauterungen zur geologischen Specialkarte des Königreichs Sachsen, Section Pirna,</ref> in Saxony.

The other minerals which have been observed in the contact rocks surrounding the Galloway granites may be very briefly disposed of. **Pyrite** occurs both in the unaltered and altered rocks. Opaque iron-ores are also often present. **Rutile** is found in the form of slender needles in the unaltered slates and shales and as yellow crystals and grains in some of the altered rocks. The development of rutile in the form of yellow crystals and grains at the expense of the needles which so commonly occur in the clay slates has been described by Beck. **Tourmaline** is rare as a contact mineral, but yellow and blue varieties occur in some of the altered shales of Knocknairling Hill.

Hornblende and **augite** are also rare. Radiating prisms of colourless **tremolite** have been observed in some small lenticles associated with the altered shales of Knocknairling Hill, and a pale green fibrous hornblende occurs in a compact hornstone-like rock associated with the normal biotite-hornfels of Barclay Hill, on the southern side of the Criffel mass. At the last-mentioned locality we find also an abnormal felspar-bearing contact-rock containing large patches of micro-poikilitic greenish or greenish-brown hornblende. It is possible, however, that in this, as well as in some other cases in the immediate neighbourhood of the granite contact, where similar hornblende occurs, the rock may be of mixed origin, and not simply the result of the crystallisation of an original sediment. Granular pyroxene has been observed in a rock from the immediate neighbourhood of the contact, about a quarter of a mile north of Kells Farmhouse, near Southwick [NX 94154 57667]. The rarity of silicates containing lime and magnesia is doubtless due to the fact that the district is comparatively free from calcareous sediments.

Altered sedimentary rocks

In the study of contact-metamorphism it is obviously of great importance to trace step by step the alteration of particular beds of rock of known composition from areas where they have not been affected by the igneous rock up to the actual contact. Over a large portion of the district this is attended with considerable difficulty in consequence of the absence of continuous exposures and the variable nature of the coarser forms of sediment which make up so large a portion of the area.

That the grits and greywackes pass into crystalline rocks, in which the original clastic structures are either partially or wholly obliterated, can be easily demonstrated, but to trace any one bed of grit from the unaltered area to its actual contact with the granite is impossible. Under these circumstances the occurrence of a well-marked zone, such as that of the radiolarian cherts and shales, is of the greatest importance. It maintains its uniform character over the whole district, and may be traced at intervals, without any possibility of error, from the unaltered area up to the junction with the granite. Mr. Horne in 1892 called attention to these facts in a communication to the Geological Section of the British Association at Edinburgh, and also described the microscopic characters of the altered rocks. The following account of the metamorphism of the rocks of this zone is based mainly on the specimens which he collected on the eastern side of the Loch Dee mass.

The unaltered chert, of which specimens may be obtained in the Garryhorn Burn, below the Lead Mines ca. [NX 53173 93261], Carsphairn, is a dark, sometimes almost black, rock (S6998), traversed by narrow white quartz veins. If the surface be moistened and examined with a lens, the black portions are seen to occur in patches and extremely thin veins. Under the microscope the rock is seen to be mainly composed of clear, crypto-crystalline silica, in which the circular and elliptical outlines, indicative of the former presence of radiolarian tests, *are* easily discernible. The silica filling the tests is somewhat coarser in crystalline texture than that forming the main mass of the rock. It differs also in another respect. The interstitial chert, when examined with a high power, is seen to be less pure. It contains minute grains and flecks, and here and there minute flakes of a colourless micaceous mineral may be detected. In addition to the crypto-crystalline silica and the impurities above referred to, the clear chert contains two or three isolated rhombs of a carbonate. The material which gives the dark colour to the rock occurs partly in thin veins and partly in the mass of the rock in the neighbourhood of the veins. It is in these turbid portions of the slide that the lattice-structure and spines of the radiolarian tests are preserved. In parts of the slide the actual substance of the tests has evidently been replaced by the opaque material. The white quartz veins are filled with micro-crystalline silica with which some black opaque material is occasionally associated. The following analysis has been kindly made for us by Mr. J. Hort Player:

Silica	91.3
Alumina	3.3
Ferric oxide	0.7
Ferrous oxide	1.4
Lime	trace.
Magnesia	0.8
Soda	0.2
Potash	0.6
Loss by ignition	0.9
	99.2

As this rock is followed towards the granite it becomes light brown or grey in colour, and takes on the character of a fine-grained quartzite. The granular structure becomes coarser as the granite is approached, and in the immediate neighbourhood of the contact the rock is often an extremely coarse-grained aggregate of quartz, having a brown colour and a peculiar resinous lustre.

The series of microscopic slides (S4953), (S4954), (S4955), (S4956), (S4957), (S4958), (S4959), (S4960), (S4961), (S4962), (S4963), (S4964), (S4965), (S4966), (S4967), (S4968), (S4969) ca. [NX 52567 91466] to ca. [NX 47823 87247] illustrates in a very perfect manner the gradual passage from compact chert to coarsely crystalline quartz-rock. In the unaltered rock the individual crystalline particles are so small as to overlap in the thinnest possible sections, and from this condition to one in which the rock is mainly composed of grains of quartz, measuring one to two millimetres in diameter, every immediate stage may be observed. The crypto-crystalline condition passes gradually into the micro-crystalline condition, and this again into the coarsely crystalline condition. The change is accompanied by the development of brown mica. This mineral first appears in the form of extremely minute scales in the more or less impure chert which fills up the space between the radiolarian casts. The purer silica, of which the circular patches are formed, did not contain the material necessary for the building up of mica. As a consequence of this it sometimes happens that the traces of radiolaria are more conspicuous in the rocks which have been slightly altered than in those which lie outside the zone of metamorphism. In the final stages all traces of the radiolaria are lost, and the larger grains contain rounded flakes of biotite, usually measuring from 0.03mm. to 0.05mm. in diameter. In addition to the small isolated and more or less rounded flakes of biotite which occur as inclusions in the quartz, we find also a few ragged flakes which attain larger dimensions. In describing the microscopic appearance of the most highly altered forms of radiolarian chert, attention was especially called to the brown resinous aspect. Microscopic examination shows that this is due to the innumerable minute inclusions of biotite contained in the quartz. The two characteristic minerals of the altered representatives of the chert are quartz and biotite and the rocks therefore constitute a special type of biotite-hornfels. In addition to the two characteristic mineral§, we find occasionally small garnets, ill-defined and often fibrous greenish products, probably arising as a consequence of the alteration of the rhombs of carbonate which occur sparingly in the unaltered rock. At the actual granite-contact, as in the specimen from Meikle Craigrarson already referred to, the coarse-grained quartz rock becomes more or less disintegrated, and detached grains of quartz, with the characteristic inclusions of biotite, may be isolated in the igneous matrix. A specimen of the coarse-grained quartz-biotite-hornfels from the immediate neighbourhood of the granite, collected at a point about 1½ miles S.S.W. of Meaul ca. [NX 48747 88514], has also been kindly analysed by Mr. Player:

Silica	93.3
Alumina	3.1
Ferric oxide	0.4
Ferrous oxide	0.8
Lime	0.1
Magnesia	0.4
Soda	0.3
Potash	0.8
Loss by ignition	0.3
	99.5

A comparison of the two analyses shows that there has been no appreciable change in chemical composition produced by the intrusion of the granite, except, perhaps, in the reduction of the amount of volatile matter. The two analyses do not differ more than two analyses of the unaltered chert may be expected to differ. The analysis of the unaltered chert clearly proves that the impurities, as they may be termed, are capable of forming brown mica.

The only effect of the granite intrusion upon the chert is thus proved to be a molecular rearrangement of the chemical constituents. The molecules of silica coalesce to form large irregular grains of quartz, and at the sane time the molecules of alumina, iron-oxide, magnesia, and alkalies combine with silica to form small scales of biotite. The actual distance traversed by any molecule during the recrystallisation of the rock is extremely small, probably not greater than the diameter of one of the mica-flakes.

The shales associated with the cherts also undergo important alteration, and in consequence of their more complex composition give rise to a greater variety of contact minerals. In their unaltered state they consist largely of extremely minute scales of a colourless or nearly colourless mica, associated with very small grains of quartz and felspar (?). Pyrite in cubes and patches, carbonates, and black carbonaceous matter are often present. A specimen from the highest exposure in Polmaddy Burn ca. [NX 49980 87358], about a mile from the granite junction (S4956), illustrates one of the early stages of metamorphism of the chert-shale series.

The rock has been more or less brecciated, and the chert and shale kneaded together. The chert has been very slightly affected; much of it still remains in the crypto-crystalline condition, and the impurities have not as yet given rise to brown mica. Radiolaria are clearly recognisable. Important changes have, however, taken place in the bands and wisps of shale. At the junction of the two rocks a large number of small garnets have been developed. These are sometimes so thickly crowded together as to mutually interfere with each other; at other times they are isolated and idiomorpliic, the intervening space being rich in secondary brown mica. The individuals vary in size from about 0.02mm. to 0.05mm. in diameter. The alteration in the central portions of the shale bands is not so marked, but here, also, garnet and brown mica have been formed. This exposure clearly proves that the shale is more readily affected by the metamorphic agencies than the chert, doubtless in consequence of its more complex composition. A further stage in the alteration is illustrated by a specimen from a point on the ridge which separates Meaul and Carlins Cairn, about 300 yards east of the granite junction (S4958). In this case the chert has become distinctly granular, resembling a very fine-grained grey quartzite, whilst the shale has been converted into a compact hornfels containing numerous small dark spots. Under the microscope the hornfels is seen to be composed of brown mica and quartz. The spots are formed of irregular individuals and aggregates of a doubtful mineral full of small more or less rounded grains of quartz. The brown mica occurs in the form of small scales which, together with quartz, make up the greater part of the space between the spots. When viewed in ordinary light the spots are distinctly visible in the thin section in consequence of the rarity of biotite. In addition to the minerals above mentioned, which make up the greater portion of the rock, we find also a few flakes of white mica.

The extreme phase of the alteration of the shales is represented by a specimen from the Kirreoch Burn, about one mile west of Carlins Cairn [NX 48099 88428]. In external appearance it is a dark brown mica-schist. The microscopic section (S7000) shows that the rock is formed of lenticles of altered chert, separated by portions of altered shale. The latter consist of brown mica, quartz, and greenish aggregates of a micaceous mineral which probably represent andalusite. The brown mica in this case occurs in much larger flakes than in the rock last described. The analysis of this rock by Mr. Player gave the following result:

Silica	64.3
Titanic acid	1.1
Alumina	15.8
Ferric oxide	1.3
Carry forward	82.5
Brought forward	82.5
Ferrous oxide	6.9
Lime	0.5
Magnesia	2.8
Soda	0.8
Potash	3.7
Loss by ignition	1.8
Sulphuric anhydride	0.4
	99.4

The Survey Collection includes a few rocks of special interest from the chert-shale horizon, which deserve detailed description. The specimen from the neighbourhood of the granite on Meikle Craigrarson ca. [NX 47823 87247] (S4969) is a thin slab measuring about three-eighths of an inch in thickness and of a dark bluish-grey colour. Long slender prisms of chiastolite may be easily recognised on the flat surfaces by means of a pocket lens. The microscopic section shows that these crystals do not occur in the mass of the rock, which is mainly composed of a granular aggregate of quartz and crystalline graphite, but only on the surfaces and in narrow bands. The original rock was doubtless composed of a carbonaceous chert interlaminated with shale, and the chiastolite has been formed in the latter. The chiastolite gives approximately rectangular cross sections, and has been more or less replaced, especially at the margins, by vividly polarising aggregates of white mica. In addition to quartz, graphite, and andalusite, the rock also contains both white and brown micas, but not in any quantity.

Specimens from the opposite side of the granite mass, about five-twelfths of a mile from the granite junction, west of Black Gairy, Buchan Hill [NX 42032 81720], Glen of Trool (S4983) and (S4984) illustrate an early phase of the alteration of black shale containing graptolites. The rock is a bluish-black hornfels, containing much pyrite, partly disseminated through the mass and partly collected in veins. The mass of the shale is crowded with fine black carbonaceous particles, which have not formed definite scales of graphite as in the rock last described. Slender prisms of chiastolite are recognised both in the hand specimen and under the microscope. A second mineral has also been developed, but it is now only represented by a brown alteration product, giving aggregate polarisation, and its original character cannot be determined.

The alteration of the grits and greywackes can only be described in general terms. The first stage is seen in the development of small flakes of brown mica between the clastic grains of quartz and felspar (S6599) ca. [NX 48396 77671]. The mica flakes increase in size and abundance as the metamorphism advances, and they are developed not only in the matrix but also in the included rock fragments. The outlines of the original clastic grains become confused and vague, and finally in the most highly altered rocks, such as those at Knocknairling Hill, no trace of the original structure remains. Brown mica is the most characteristic contact mineral. It occurs in irregular scales, several of which usually occur together. As a rule, it is markedly allotriomorphic with respect to the quartz; in other words, it plays the role of interstitial matter. In some cases, however, it occurs in inclusions in the quartz grains in detached and usually rounded scales.

The grits and greywackes show great variability in the size of their constituent particles. This feature is seen in all except the most highly altered rocks. As the metamorphism increases the outlines of the fragments become more or less vague and indistinct, but their former presence is clearly indicated by the occurrence of patches rich and poor in brown mica.

Of the original constituents felspar is perhaps the most important after quartz. This mineral appears to be sometimes destroyed and sometimes regenerated in the process of metamorphism. It is very frequently represented, as Messrs. Bonney and Allport pointed out, by micro-crystalline aggregates, associated with ill-defined flakelets of a micaceous mineral. At other times it appears cloudy, but with individual action on polarised light, and in a few cases it is present as a water-clear mineral in connection with quartz (S2549) ca. [NX 47086 96221]. In addition to the mineral fragments, the grits and greywackes frequently contain bits of felsitic, trachytic and andesitic rock, fragments of shale and fine grits, and occasionally radiolarian chert. It is not possible to trace step by step the alteration of the different varieties of rock, and we are, therefore, often in doubt as to the original character of some of the fragments in the highly altered strata. However, the felsitic fragments may frequently be recognised in the metamorphic rocks (S690) ca. [NO 57449 36721], and they show that here and there small flakes of the ubiquitous brown mica have been developed even when the micro-structure of the main mass has been little, if at all, changed. The andesitic fragments lose their characteristic structure and give rise to much brown mica. The shale fragments also show a great development of brown mica, with which some white mica is occasionally associated.

So far we have been referring only to rocks that surround the most northern of the three large granite masses. The greywackes and grits rarely lose all trace of clastic structure, even when the recrystallisation is complete. A higher grade of metamorphism appears to be reached on the borders of the Cairnsmore of Fleet mass, in the neighbourhood of New Galloway. The altered rocks of this area have been microscopically examined and described by Miss Gardiner, and the result of the examination of the material collected by the Geological Survey has merely served to confirm the accuracy of her work. A series of fine-grained grits and shales can be followed at intervals from a comparatively unaltered condition to one in which complete recrystallisation has taken place. The more argillaceous members of the stratified series pass into chiastolite-schists, and can be followed close up to the junction with the granite. These rocks do not present any features of special interest. The alteration of the gritty beds is more remarkable. The final product is a coarse-grained gneissose rock, mainly composed of brown mica, quartz, sillimanite, and a little felspar, without a trace of the original clastic structure. Such a rock may be termed a gneissose garnet-sillimanite hornfels with two micas. The general appearance of the rock under the microscope is well represented in fig. 2, (Plate 23), illustrating Miss Gardiner's paper. Although specimens may be obtained of somewhat coarser texture, the Survey specimen (S6604) [NX 62249 76501] may be taken as a type of this rock. In the hand specimen it is a dark, medium-grained, foliated rock. White mica is conspicuous on the surfaces parallel to the foliation. Notwithstanding the fact that the white micas are arranged with their flat surfaces approximately parallel to each other, the rock does not cleave readily in the direction of foliation. Under the microscope white mica is the most conspicuous mineral. It occurs in ragged plates, which then contain garnet, quartz, and sillimanite as inclusions. Single individuals, measuring one or two millimetres across, are not uncommon. The plates are sometimes isolated, but more frequently two or three occur together. The biotite also occurs in ragged plates, but the individuals are smaller. The pleochroism is strongly marked, and in the position of maximum absorption the mineral appears a very dark brown. Pleochroic halos are present. Garnet occurs in the form of rounded and irregular grains, and also as idiomorphic crystals. The individuals vary in size, those measuring about 0.3mm. in diameter being very common. In other specimens of the stme rock the average size is larger. Inclusions of a colourless mineral, probably quartz, are usually numerous, especially in the central portions of the mineral. The mineral appears red in the hand specimen, but in the thin sections is nearly colourless. The sillimanite is developed in the form of very fine needles, which are often aggregated in tufts. They are especially abundant in the white mica, but occur also in the quartz. Quartz occurs in irregular grains, and sometimes forms a coarse micro-crystalline mosaic. Felspar is rare. It may be recognised by its refractive index, which is lower than that of the balsam in which the slide is mounted, by its biaxial figure, and by the occasional presence of lamellar twinning.

As this rock is traced away from the granite, a marked diminution in the size of the white mica is observed. A good illustration of this is furnished by a specimen from a point below the Cairns and near the stone dyke (S6605) [Knocknairling Hill]. The rock is a garnetiferous mica-schist. The schistosity is more marked than in the specimen from the immediate neighbourhood of the granite, and the white micas, instead of appearing as individual plates, form a glaze on the flat surfaces. The garnets are, however, somewhat larger in this specimen than in the last.

In the immediate neighbourhood of the granite the garnet sillimanite hornfels contains lenticles of a pink rock essentially composed of quartz and garnet.

The alteration of the shale bands into more or less schistose rocks containing chiastolite has been already referred to. Associated with these shales are some thin bands and lenticles of a harder rock, in which radiating groups of crystals may be recognised with a hand lens (S6601) [Knocknairling Hill]. Under the microscope these crystals can be identified as tremolite. The other minerals recognisable are quartz, mica, pyrite (abundant), and black carbonaceous dust.

In the immediate neighbourhood of the granite occurs a black graphitic schist (S6602) [Knocknairling Hill], containing micro-poikilitic white mica crowded with minute particles of carbonaceous matter, and not easily distinguishable from the main mass of the rock, which consists mainly of quartz and carbonaceous dust, without the aid of polarised light.

It appears from what has been already said as to the contact-metamorphism surrounding the granite masses of Galloway that the district abounds in illustrations of the alteration of the various types of non-calcareous sediment. Limestones are, however, conspicuous by their absence from the contact zones. Under these circumstances special interest attaches to a compact green rock occurring in impersistent bands and lenticles in a biotite-hornfels, close to the junction of the Criffel mass, on the south-east of Barclay Hill, about 4¾ miles S.S.E. of Dalbeattie. This rock (S6598) ca. [NX 87273 54919] probably represents in an altered form one of the impure calcareous rocks associated with the Upper Silurian deposits of this area. It is the "come verte" of French petrographers. Under the microscope it is seen to be a very fine-grained aggregate of a colourless mineral, presumably quartz, hornblende a colourless garnet occasionally showing signs of double refraction, and some opaque grains of iron-ore. The hornblende is allotriomorphic, and the larger patches show micro-poikilitic structure. All the constituents are extremely small, and the true character of the rock can only be determined by the use of very thin sections and a high power. It would be interesting to determine whether any felspar is present, nut owing to the extremely fine grain of the rock this is impossible. We have now to describe the effects of the granites upon the igneous rocks of Lower Silurian age.

Altered igneous rocks

Arenig lavas altered by granite occur near New Cumnock and at the margin of the Carsphairn mass. Those from the former locality (S6530), (S6531), (S6532), (S6533), (S6534), (S6535), (S6536) [NS 65192 13070]; (S6537) [NS 651 131], (S6538) [NS 93770 23499] are coarse-grained, massive, and often mottled with dull green and pink tints. Traces of an amygdadolial structure may frequently be seen in the hand specimens.

When examined under the microscope the mineralogical composition of the rocks is seen to vary in different specimens, and even in different portions of the same section. The following minerals have been recognised in the series taken as a whole: hornblende, augite, biotite, garnet, felspar, sphene, epidote, black opaque iron-ores, pyrite, haematite, carbonates, chlorite.

The hornblende is usually brown, but green varieties have also been observed. It occurs in small crystals, with more or less rounded angles; also as grains and as large micro-poikilitic patches crowded with small felspars and other minerals (S6531). The augite is pale in colour and faintly pleochroic in pale green and violet-brown tints. It is usually present in the form of small grains and irregular patches, but traces of the orthopinacoid, clinopinacoid and prism faces have been observed.

The common type of biotite is greenish in colour. It may be present either as small scales or as large micro-poikilitic patches. The reddish brown biotite, which is so common as a product of contact-metamorphism, has been observed only in one specimen (S6538) [NS 93770 23499]. Here, however, it occurs in great abundance, and forms, together with felspar, the main mass of the rock.

Garnet is especially characteristic of the series, taken as a whole, although it is not present in every specimen. This mineral is found in the mass of the rock, and also in veins and amygdaioidal cavities it may be deep brown or colourless, and it is worthy of note that the colourless varieties invariably show double refraction. Pale brown varieties are the most common. The individuals are aggregated together, and but rarely show signs of idiomorphism. They frequently form zones round the amygdaloidal cavities, and sometimes extend into these cavities. In the latter case they increase in size, lose their colour, become doubly refractive, and sometimes idiomorphic. It is interesting to note that the garnet of these rocks is quite distinct from that of the altered grits and shales. On the other hand, it resembles the garnet often found in metamorphosed calcareous rocks. It is highly probable that it has been developed only in those rocks which were decomposed before the intrusion of the granite, and in which carbonates had been extensively developed.

Felspar occurs either as aggregates of irregular grains or as large micro-poikilitic patches. The latter are certainly orthoclase. The substance of this felspar, which forms as it were the ground mass of several specimens and shows uniform extinction over large areas, is often perfectly limpid and entirely devoid of twinning, but it is so closely crowded with the other constituents of the rock that its exact determination is attended with considerable difficulty. The fine powder of the rock was searched for a long time in the hope of finding minute M-flakes, but no reliable results were obtained. A solution of borotungstate of cadmium, having a refractive index intermediate between that of orthoclase and albite, was then prepared. When tested in this solution by the Becke-method, the mineral in question was found to agree with the orthoclase, and at the same time one or two M-flakes were accidentally met with. These gave confirmatory evidence. Seeing that the original rocks were either intermediate or basic in composition there can be no doubt that this felspar is a product of metamorphism. This, indeed, might be inferred from its relation to the other constituents quite apart from its composition. Further evidence of the secondary development of felspar is furnished by the fact that it may occasionally be observed in the amygdules. In addition to the secondary felspar, which is always present, one specimen contains the relics of felspar-phenocrysts. These are zoned by garnets which appear to eat into and partially occupy the space originally filled with felspar.

Sphene is almost always present in considerable abundance. It occurs in the form of minute colourless grains, often clustered together, and, more rarely, as larger grains, which sometimes assume a spindle-shaped form.

Iron-ores, zoned with colourless sphene, may be observed in one or two specimens.

Epidote is not a common constituent. It may occasionally be seen associated with a carbonate in the central portions of some of the amygdules. Carbonates, when present, occur as large crystalline patches moulded upon the other constituents. They probably represent the secondary carbonates, due to the decomposition of the original rocks; but, if so, it is clear that they must have undergone recrystallisation under the influence of the granite. The other minerals do not call for detailed description.

With the exception of the felspar phenocrysts in one specimen (S6530), and the amygdaloidal structures in several others, the original structures of these rocks have entirely disappeared. The aagite, hornblende, garnet, sphene, and the greater part of the felspar are of secondary origin, and they have been developed in such a way as to destroy the original micro-structure of the rock. The only rocks in any way resembling those above described are the metamorphosed basic rocks surrounding the shap granite (See Quart. Journ. Geol., Soc., vol. xlix. (1893) Supplementary Notes on the Metamorphic Rocks around the Shap Granite: by Messrs. Harker and Marr). The two groups resemble each other in containing garnet of the same type, sphene, augite, and hornblende, but the micro-poikilitic orthoclase, which forms a peculiar feature in many of the Scottish rocks, is absent from those of Shap.

The following table represents the distribution of the minerals in the specimens from Polshill Burn [NS 65180 13061]:

Altered Arenig lavas

	Hornblende	Augite	Biotite	Garnet	orthoclase	Felspar (?)	Sphene	Epidote	Iron-ores	Carbonates	Chlorite	Aggregates of a colourless undetermined mineral

(S8530)				x	x	?	x	x	x	x	x		Amygdule filled with carbonate and epidote and zoned with garnet. Felspar phenocryst zoned with garnet.
(S6581)	x	x	x	x	x		x		x			x	Orthoclase in large water-clear un-twinned micro-poiklitic patches. Iron-ores zoned with sphene.
(S6532)		x	x	x	x		x	x				x	Orthoclase as above.
(S6533)			x	x	x		x		x		x		Pyrite.
(S6534)	x	x	x		?	x	x		x				Micro-poikilitic hornblende.
(S6535)	x	x		x	x		x			x		x	Orthoclase as in (S6531). Garnet often doubly refractive.
(S6536)	x	x	x	x	x		x					x	Orthoclase as in (S6531), sometimes crowded with granular pyroxene.
(S6537)			x	x	x	x	x		x	x	x		Secondary felspar in amygdules.

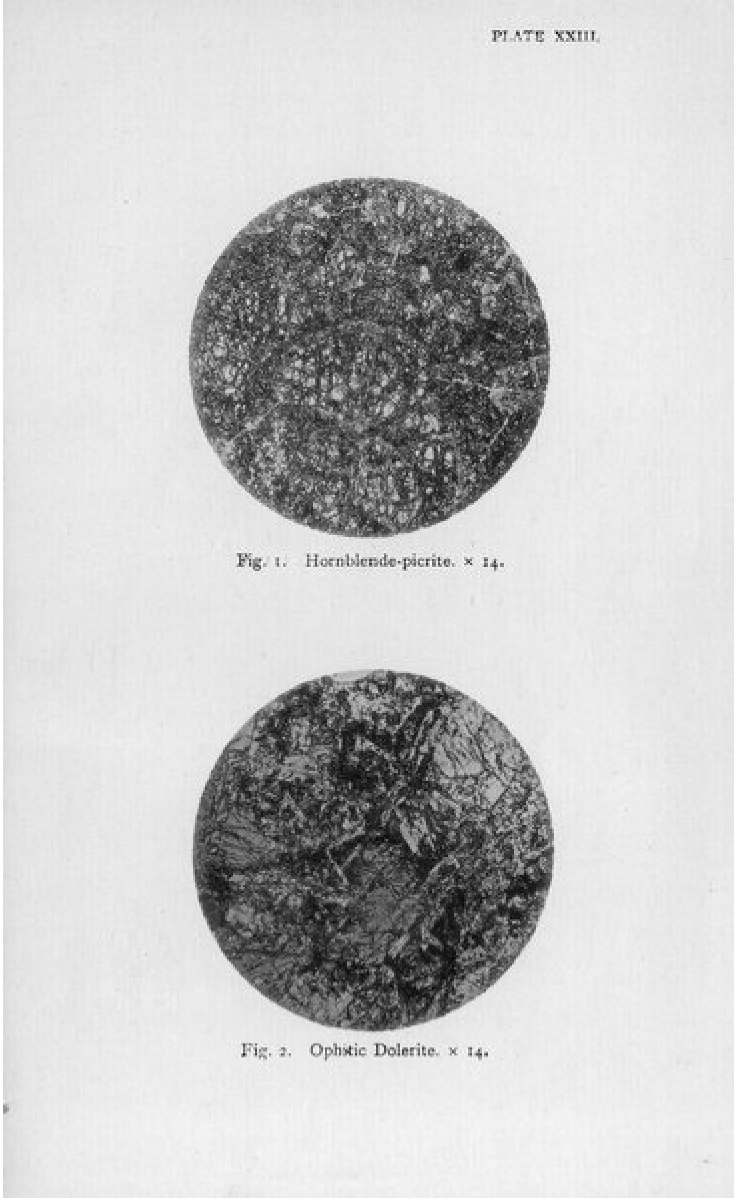
(S6538)	x	x	x	Pale brown and pale green biotite in small scales. Micro-crystal■l aggregate of felspar.

The altered Arenig lava from the edge of the Cairnsmore of Carsphairn granite (S7171) is composed of small whitish spots and patches with somewhat vague boundaries in a fine-grained dark matrix.

Under the microscope the whitish spots are seen to represent, at any rate in most cases, amygdaloidal cavities. The central part of the spot is usually occupied by a patch of crystalline calcite with irregular borders. The marginal part is an aggregate of felspar. The crystalline calcite is moulded on the felspar. Granules of colourless sphene and crystals or grains of epidote occasionally occur in association with the calcite and felspar; so also do malacolite, hornblende, and garnet, though more rarely. The ground-mass is essentially composed of felspar and hornblende. These two minerals form a confused aggregate The individuals of hornblende are small, and without any marked idiomorphism, although they frequently show a tendency to elongation in the direction of the vertical axes; they are not large enough to show good cleavages. The colours are: α, yellow; β and γ, olive-green. The hornblende lies in a matrix of felspar which cannot be definitely determined. Definite crystallographic boundaries are absent, but the individuals sometimes show a tendency to elongation in one direction. Colourless grains of epidote or malacolite also occur in association with hornblende and felspar. Grains and crystals of sphene may also be occasionally observed. From the above description it appears that the original rock has been recrystallised, and the true igneous structure has been almost entirely obliterated in the process.

Another specimen from Poldores Burn, Carsphairn (S7172) [NX 61125 97286], is a medium-grained, dark, massive rock, composed of lath-shaped plagioclase, ophitic brown hornblende, biotite, and iron-ores.

The original rock was doubtless an ophitic dolerite, probably intrusive. The augite has been changed to dull brown hornblende without well-marked cleavages. Large patches extinguish uniformly, and bear the same relation to the lath-shaped felspar as the augite of the original rock. Biotite occurs in aggregates of small scales, which are not distributed uniformly throughout the rock. This rock differs from the last in that the original structure has been largely retained.



(Plate 23) 1. (S6432) Hornblende-picrite. Thin dyke-like vein in serpentine, 200 yards west of Balhamie Burn. Magnified 14 diameters. The dominant mineral is olivine, occurring in large grains, and traversed by the usual anastomosing veins, along which magnetite has been deposited. The spaces between the grains are now occupied by brown hornblende and alteration products after felspar. The amount of felspar originally present must have been very small. 2. (S6470) Coarse-grained ophitic dolerite, east side of Byne Hill, 6 yards from edge of mass. Magnified 14 diameters. The conspicuous patch near the centre represents an allotriomorphic grain of olivine. The other minerals art augite and more or less turbid plagioclase. A lobe of the olivine grain is seen in contact with augite in the lower or south-east quadrant, and the latter mineral is moulded on the former. As the olivine is clearly allotriomorphic with respect to the felspar, the order of consolidation in this rock has been basic plagioclase, olivine, augite. Fig. 1. Hornblende-picrite. x 14. Fig. 2. Ophitic Dolerite. x 14.