

NO. IV.—THE PITCHSTONES OF SOUTH ARRAN. By ALEXANDER SCOTT, M.A., B.Sc.

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THE pitchstones of Arran have been so well known for more than a century that further description may seem to require an apology. Except for Judd's description of the Drumadoon and Cir Mhor occurrences,<sup>1</sup> most of the previous investigations have dealt with the Corriegills rocks. The object of the present paper is to give a description of the glassy rocks and the felsites associated with them, which are found outwith the area treated in the Geological Survey memoir on North Arran, and to discuss shortly several of the more striking characteristics which they exhibit. The occurrences considered include the Monamore Glen sills and dykes, the Glen Ashdale composite dyke, the series of intrusions in the neighbourhood of Tighvein and the Burican pitchstone.

THE MONAMORE PITCHSTONES.

The earliest notice of this series of intrusions occurs in Bryce's "Geology of Arran." In the edition published in 1859 no mention is made of it, but in the third edition, published about 1865, he describes two beds of pitchstone in "Moneadmoor Glen," associated with "claystones, hornstone, quartz-rock, and porcellanite."<sup>2</sup> Zirkel,<sup>3</sup> in his account of his journeyings in the Western Isles, mentions incidentally, in his description of the Corriegills and Tormore dykes, the same two intrusions, and notices that they contain thicker spherulites than is usual in this type of rock, and small green hornblende prisms, while associated with them is a "hornsteinähnliche felsit." Similarly, Allport<sup>4</sup> refers to them, but gives no details.

This series of intrusions comprises one felsite dyke and three pitchstone sills. The latter have been intruded along the

<sup>1</sup> *Q. J. G. S.* (1893), xlix., pp. 536-566.

<sup>2</sup> "Geol. of Arran," 3rd and 4th editions, pp. 156-158.

<sup>3</sup> *Zeit. der deutsch. geol. Gesellschaft* (1871), xxiii., p. 41.

<sup>4</sup> *Geol. Mag.* (1872), ix., pp. 536-545.

bedding planes of the Lower Triassic sandstones, and are well exposed in the bed of the stream which runs through the glen. The dyke occurs about 400 yards above the bridge which carries the Whiting Bay-Lamlash road over the burn, and it cuts through the sandstones, here dipping upstream at an angle of 10 degrees, in an approximately north and south direction. The dyke-rock is apparently a dark flinty felsite of rather fine texture, and somewhat jointed and broken. About 20 feet further upstream the first pitchstone sill occurs (see fig. on p. 31). The lower part consists of a bottle-green, non-spherulitic pitchstone with good conchoidal fracture, and joint planes so numerous that any attempt to determine its general direction is hopeless. This, however, is immediately overlaid by a light-coloured devitrified rock, which, at its upper margin, obviously passes, sill-wise, beneath the sandstones; and thus the whole, the thickness of which is about 30 feet, would seem to be a composite sill intruded in the sediments. Passing upstream from this place, there is an interval of a few yards of sandstone, and then, overlying this, is the second pitchstone sill. This is more complicated than the first one, and shows a considerable variety of rock, which, however, is always acid in composition. At the base there is about 25 feet of green pitchstone, immediately followed by 4 feet of hard green platy felsite, which, in turn, is succeeded by 9 feet of spherulitic pitchstone passing into a banded variety, and finally to a much devitrified rock of felsitic appearance. The last intrusion occurs at the Woollen Mill, and consists of a brown banded glass with abundant spherulites, and showing the effects of considerable devitrification, particularly towards the margins. At the upstream edge it seems to abut steeply against the sandstones, but at the lower it obviously overlies the sediments, in this case also a band of sandstone.

#### *Microscopic Characters.*

The rock of the dyke is a fine-grained basalt, with numerous phenocrysts of quartz and felspar, and xenoliths of a darker rock, also of basaltic affinity. As it has obviously no immediate

relation with the pitchstones, and is probably of an earlier date, it will not be further described here.

The lowest pitchstone has a dusty brownish groundmass, in which are embedded scarce phenocrysts and numerous microlites. The former consist of felspar, which is usually a plagioclase approximating to normal oligoclase, magnetite, and some hydrated iron oxides which are decomposition products of a pyroxene. This rock has the banded structure which was noticed by Allport in the Tormore and Drumadoun<sup>5</sup> pitchstones, and which is also present in many of the Corriegills examples. The bands are of two kinds, a comparatively narrow one alternating with one several times as broad. The former consists of a clear glass with numerous rod-shaped crystallites, but free from complicated arborescent forms. These rods seldom appear single, but seem to be composed of an aggregate of belonites arranged with their axes in approximately parallel directions, and with the shortest in the centre, so that the ends present a bifurcated appearance and the whole resembles the crenulite<sup>6</sup> of Rutley. These are too small for the discrimination of cleavage, &c., but they are green in colour and anisotropic, with an extinction angle which varies from zero to 30 degs. By the growth of two or more of these from a common centre, cruciform and stellate forms develop, and, indeed, are more common than the simple forms. A prominent characteristic of these bands is the presence of innumerable idiomorphic crystals of magnetite, generally in euhedral cubes, and accompanied by small belonitic structures growing out from them in radial directions.

In the other bands the clear glassy base is rendered a dusty brown colour, owing to the presence of numerous greenish longulites, which give a low extinction angle, and are probably of a hornblendic nature. In addition, there are many larger microlites, each surrounded by an area of colourless glass. Structurally these may be divided into two types, which are well known from the descriptions of Zirkel,<sup>7</sup> Allport,<sup>8</sup> Rosen-

<sup>5</sup> *Geol. Mag.* (1872), ix., pp. 1-10.

<sup>6</sup> *Min. Mag.* (1891), ix., p. 261, &c.

<sup>7</sup> *Zeit. der deutsch geol. Gesellschaft* (1871), xxiii., pp. 42-46.

<sup>8</sup> *Geol. Mag.* (1872), ix., pp. 1-10, 536-545.

busch,<sup>9</sup> &c.<sup>10</sup> While both have composite main axes of parallel belonites arranged in a step-like fashion, they differ in the arrangement of the subsidiary axes. In one type these grow out from the principal axis at all points, and the skeleton crystal ultimately assumes an arborescent form, while in the other type the outgrowths are confined to the two ends of the principal axis, which otherwise is free from excrescences.

Passing upwards from the base, the flow structure, as indicated by the parallelism of the belonites becomes more pronounced and devitrified patches begin to appear. The latter are much stained with iron oxides, and have usually at their centre a crystal of felspar, which is often so corroded that little of it remains. Another exposure of this pitchstone a few yards to the south shows these structures much more prominently. The basal pitchstone of the second sill very much resembles this one, save that the majority of the microlites assume a different form, being composed of radial bunches of rods, usually curved, and growing out from a crystal of quartz or sanidine or a single belonite axis. In the latter case the microlites are similar to the axiolites of Zirkel.<sup>11</sup> Arculites<sup>12</sup> are also present, but the other forms predominate.

The upper rock of the first sill is an indistinct, much devitrified glass with decomposed microlites, phenocrysts being rare, and always corroded. A remarkable feature is a number of parallel bands, which cross the rock in a direction approximately coincident with that of the microlites. The structure is somewhat complicated, but a prominent characteristic is a series of longitudinal aggregates of green anisotropic crystals, two occurring side by side in each band, surrounded by a yellowish-brown area of still smaller crystals. Where a phenocryst occurs in a band, the latter widens out and passes round the former, which in many cases has been resorbed, and is represented by a devitrified area showing spherulitic extinction in polarised light, as do the outer margins of the bands. Most of the phenocrysts are aggregates of quartz and felspar, while

<sup>9</sup> Micro. Physiog. d. massigen Gest., p. 700, &c.

<sup>10</sup> Teall, Brit. Petrogr., pp. 344-347, &c.

<sup>11</sup> Micro. Petr., 40th par. (1876), pl. vi., fig. 2.

<sup>12</sup> Rutley, *loc. cit.*

several narrow felsitic veins of these minerals traverse the rock in irregular directions.

The second pitchstone of the upper sill is a banded rock, which originally was probably very like the non-porphyrific variety of the Corriegills rocks,<sup>13</sup> but which is now devitrified to a considerable extent. The glassy groundmass is filled with belonites and skeletal microlites, while a few anhedral crystals of feldspar and augite occur, the former showing very fine lamellar twinning, and resembling anorthoclase. The augite and the microlites have been altered sometimes to iron oxides, and the glass devitrified, chiefly along flow bands and in subsidiary directions perpendicular to these. The central axis of these "schlieren" bands is a narrow line of green non-pleochroic chloritic crystals like those occurring in the previous rock. On each side is a broad, clear area, with low double refraction, traversed by numerous secondary axes, and composed of spherulitic masses of quartz and feldspar. This becomes more dense and opaque towards the outside margins, which are usually delineated by an aggregate of somewhat decomposed microlites standing out in relief against the undevitrified glass. That this development of crystalline structure, which also appears round the phenocrysts, took place long after the formation of the microlites, and hence after the rock had cooled, is shown by the fact that these are found independently of the bands, and, indeed, often crossing the boundaries of the latter. Passing upwards from the base, the amount of devitrification decreases, and the upper part is a perfectly fresh and unaltered microlitic pitchstone. It is traversed by a large number of microscopic lines—about fifty to the centimetre—which are approximately parallel, and, at first sight, look like scratches.\* They are made up of aggregates of dark green crystals of a hornblendic nature, resembling those of the upper part of the first sill. In the latter rock the green crystals, originally pyroxene or hornblende, seem to have altered to chlorite during the devitrification of the rest of the base. While in both cases

<sup>13</sup> v. Harker, *Petrology*, 4th ed. (1908) p. 119, footnote.

\* That these are not scratches is shown by their perfect parallelism and by the preparation of other slides—on rotating discs—which showed the same structures.

the microlites cut through the bands in all directions, the unaltered rock shows that their development is anterior to the crystallisation of the base, as incipient devitrification is only found locally where the glassy margin of the band is altered to a cryptocrystalline aggregate.

The uppermost rock of this sill may be described as a devitrified felsite, and changes in the space of a few inches from a dark, spherulitic, banded variety to a light green one, with no banding or spherulites visible in the hand-specimen. It has originally been a non-porphyrific pitchstone with numerous microlites, which are now much decomposed and changed to amorphous hydroxide of iron, while the groundmass is made up of a devitrified mass of quartz and felspar—the former predominating—which is sometimes spherulitic, sometimes apparently granophyric. The dark layers in the hand-specimen are represented in thin sections by lighter non-microlitic bands of felsitic appearance. The rock is exceedingly siliceous, and seems to be made up of quartz and amorphous limonite, with subordinate felspar, which cannot be discriminated owing to the cryptocrystalline structure.

The Woollen Mill rock presents a more remarkable appearance than any of the other Monamore intrusions. The small portions of the base which remain undevitrified show that it was originally a colourless glass with many large crystals of felspar, which contain numerous orientated inclusions of the matrix, and are partly sanidine and partly a basic oligoclase. A few crystals of magnetite may represent original pyroxene or hornblende, but the greater part of the iron has separated in an amorphous form during devitrification, as in many cases the isotropic glass is coloured a deep brown by limonite and hæmatite staining. There are numerous ferromagnesian belonites, which seem to be of two kinds, one extinguishing at an angle of about 30 degs., while the other shows practically straight extinction. The rock is very much altered by devitrification, which has commenced along cracks and schlieren bands and round the felspar crystals, and is pronouncedly spherulitic. The outside margins of the devitrified areas are delineated by a continuous series of elliptical arcs of dark limonitic material, with a lighter band immediately inside these. In a fresher sample of this

rock, found in the Rutley collection, this margin is composed of green crystals, apparently of a chloritic nature. In other parts of the rock incipient devitrification has produced many elaborate radial and spherulitic structures.

#### THE GLEN ASHDALE COMPOSITE DYKE.

The dyke on the south side of Glen Ashdale is exposed on the escarpment which marks the boundary of the Dippin teschenite. It strikes approximately north-north-west, and can be traced for about 70 yards to the southward, but cannot be followed on to Torr an Loisgte, which is composed of another branch of the Dippin sill. The dyke is composite, the two marginal parts, each about 3 feet thick, being pitchstone, while in the centre is about 8 feet of felsite. The hade is about 40 degrees to the south-west, and the rock is little jointed or broken, while the junction between the two varieties is perfectly sharp, there being no gradual transition from the one to the other. Megascopically the marginal rocks are very similar in appearance, both being green pitchstones with subconchoidal fracture. The eastern one, however, has not so pronounced a lustre as the western, and is somewhat lighter in colour, while both are traversed by a number of dark parallel bands. The central rock is a grey spherulitic felsite, in which small quartz and felspar crystals can be detected. The arrangement of the spherulites tends to produce a banded appearance, while the rock has an irregular fracture, and is often coloured brown, owing to limonite staining.

#### *Microscopic Characters.*

The "eastern" pitchstone is composed of a glassy base crowded with rod-shaped microlites and smaller "dusty" belonites, and with numerous phenocrysts of quartz, felspar, pyroxene, and magnetite. The quartz is generally found as well-shaped crystals surrounded by hyalite areas with "brush" extinction, and an intermediate tridymite layer as described by Judd,<sup>14</sup> although in this case the structure is not so pronounced

<sup>14</sup> Judd, *Q.J.G.S.* (1890), xlvii., p. 380.

as in the Cir Mhor rock. Microlites are common in the inner of the two hyalite bands, but very scarce in the outer. The felspar occurs as euhedral triclinic crystals with the characteristics of oligoclase, and having, in common with the quartz, frequent inclusions of apatite, magnetite, and augite. The pyroxene is an ægirine augite of intermediate composition showing slight pleochroism. The phenocrysts are found in glomeroporphyritic aggregates, and have undoubtedly been formed under plutonic conditions, the pyroxene being surrounded by the quartz and felspar.

The larger microlites are single green prisms with no pleochroism and a good cleavage, which is apparently rectangular, while the extinction varies from 40 to 50 degrees. They show the properties of a pyroxene, and there is no doubt as to their identity as one of that group. Subordinate to these are clusters of cruciform growths of smaller belonites, which average in length '01 millimetre, while the larger microlites vary from '6 to '03 mm. The base is otherwise a colourless glass, save where, in the neighbourhood of corroded quartz crystals, devitrification has been induced, probably by local silicification following on re-solution of the quartz. The rock of the western margin is very similar, except that the microlites are smaller, averaging '06 mm., while they are invariably surrounded by a clear "court of crystallisation."

The central rock consists of quartz and felspar phenocrysts in a cryptocrystalline aggregate of the same minerals. The quartz occurs in well-defined hexagonal crystals, with rounded angles, while the felspars are likewise euhedral, and are mainly sanidine, together with a little anorthoclase. The base is a characteristic granophyric intergrowth, except in the neighbourhood of the quartz crystals, which are invariably surrounded by a spherulitic development consisting of brown radial fibres interspersed with a number of decomposed belonites. There are two concentric bands of these fibres, differing in refractive index and double refraction, which in both cases is lower than that of quartz. The fibres are probably hyalite, and the variation in the optical properties is due to a difference in the water content, the brown colour being caused by limonite. The structure is not found round the felspar nor the small,



almost colourless, ægirine which is occasionally present. Hæmatite is also found in skeletal forms, and may be pseudo-morphous after ilmenite.

#### THE TIGHVEIN DYKES.

The series of dykes which occur to the south and east of Tighvein have many things in common, and may be considered together. The An Sloc intrusions have been treated in detail by Corstorphine,<sup>15</sup> and little can be added to his description. These are two parallel dykes trending in a north-west and south-east direction, one at the confluence of the An Sloc and a small tributary on the north side, and the other some distance further up the main stream. The former cuts through the felsite porphyry, and the latter through the basalt which composes the southern part of the Tighvein complex, and the dykes are indifferently exposed in the centre of an area covered by peat. Both rocks are green pitchstones with splintery fracture, the upper showing quartz and felspar, while the lower has a dull, aphanitic appearance.

Microscopically the rocks show phenocrysts of quartz, felspar, and pyroxene in a groundmass of "microlitic" glass. The felspar is the most abundant, and comprises plagioclase and subordinate orthoclase and microcline. The quartz and felspar occur in subhedral crystals, with numerous inclusions of glass, augite, enstatite, zircon, and rutile. The pyroxene is found as small euhedral crystals of augite, which is often twinned, and strongly pleochroic enstatite. Rutile altering to leucoxene, pyrites, and magnetite occur as scarce accessory minerals.

The groundmass may be divided into three parts—

(a) Layers of glass rendered opaque by the presence of innumerable longulites and occasional skeletal forms.

(b) Lighter bands, crowded with belonites arranged in radial aggregates, and containing plumose microlites.

(c) Spherulitic areas round quartz and felspar. These are usually bordered by a dark brown ring, with a similar, but double, band in the middle of the crystalline aggregate. Corstorphine<sup>16</sup> identifies the minute particles which make up

<sup>15</sup> Tschermak's Min. Mitt. (1894), xiv., pp. 480-450.

<sup>16</sup> *Loc. cit.*

these bands as rhombohedral crystals of chalybite formed by the decomposition of glass under the influence of carbon dioxide. It seems more probable that they are aggregates of hæmatite and limonite as decomposition products of femic minerals similar to those described above in the margins of devitrified parts.

About half a mile east of these intrusions another pitchstone dyke cuts through the felsite in an east and west direction near the source of the Allt nan Clach, a tributary of the Kilmorie Water. The rock closely resembles those described above, and a separate description is unnecessary.

Another dyke, unmarked in the one-inch Geological Survey map, is seen in the eastern branch of a tributary of the Allt Dhepin, about 600 yards west of Loch na Leirg. Its thickness cannot be measured, as only one face is exposed, forming a small waterfall in the stream, and trending in a N.N.W. direction. It is a greyish-black porphyritic pitchstone, with numerous light-coloured spots, and a pronounced platy fracture parallel to the vertical edge. It is traversed by numerous thin veins of felsite up to 3 inches in thickness, and roughly parallel to the walls of the dyke. The dyke, with a north-west and south-east direction which outcrops on the path about one-third of a mile south-west of the Urie Loch, is identical with the above, and would seem to be its continuation. The maximum thickness here exposed is about 20 feet. Microscopically the rock is a pitchstone porphyry with phenocrysts of quartz, plagioclase with regularly arranged inclusions, pyroxene, which is partly a zoned augite and partly enstatite, olivine,<sup>17</sup> and magnetite. There are two generations of crystallites in a glassy base, the larger being green pyroxenic belonites with no pleochroism and a high extinction, and the smaller, brown indefinite longulites. The latter occur in aggregates as the outer margin of a band of hyalite, which is usually found round the euhedral quartz and felspar, but not round the pyroxenes. As in the Cir Mhor rock, a narrow layer of tridymite occurs in the hyalite, but very near the outer margin. The base of the longulitic bands is occasionally anisotropic, and has probably undergone devitrification to some extent.

The felsite, which traverses the main rock, has a blue-grey

<sup>17</sup> For description of olivine, *see* page 26.

flinty appearance, altering in parts to a light-coloured modification, and occasionally porphyritic. Microscopically the rock consists of a cryptocrystalline groundmass with phenocrysts of quartz, felspar, decomposed pyroxene, olivine,<sup>18</sup> and magnetite. The quartz is found as perfect euhedral crystals surrounded by hyalite, but the tridymite is absent. The felspar is apparently a basic oligoclase which is very much sericitised, while the groundmass is mainly a felsitic intergrowth of quartz and felspar, with, in some parts, a graphic structure, in others a spherulitic. Decomposed microlites are common, and a little uncrystallised glass is also present.

The only other pitchstone which will be described is the Burican rock, which outcrops in Sliderry Water just above Glenrie Bridge. The pitchstone forms a ledge about 20 feet thick at the junction of a felsite sill and the sediments, and is probably the upper part of the sill, which here seems to come up along the junction of the Upper and Lower Trias.

Microscopically the rock is a glass rendered opaque by minute microlites and with many aggregates of phenocrysts, comprising quartz, felspar, pyroxene, olivine, and magnetite. The quartz and felspar, which is a rather basic oligoclase, are found as euhedral crystals with abundant inclusions, which are often regularly orientated. Round the crystals occurs an anisotropic double band, which seems to be rather decomposed hyalite, while the dark band in the middle may represent tridymite. The pyroxene is an ægirine augite with a fairly high extinction, and hence much nearer the augite end of the series. The larger belonites are likewise pyroxene, with the same properties, and are surrounded by a clear area of glass, as in the western margin of the Glen Ashdale dyke. Forms intermediate in size between the belonites and the phenocrysts are also found, so that there is no doubt that the belonites are augite. In addition, there are a number of greenish crystals with high refractive index, and altering to serpentinous material. They resemble olivine very much, and a careful measurement of their double refraction proved them to be fayalite. The crystals show slight pleochroism from green to greenish-yellow, and alter in part to serpentine, in part to hæmatite, which is more trans-

<sup>18</sup> See page 26.

lucent than that mineral usually is. The olivine which is mentioned above in the description of the Allt Dhepin rock shows the same characters. Olivine is exceedingly scarce in acid rocks, and it is somewhat difficult to account for its co-existence with quartz in a pitchstone. Iddings<sup>19</sup> describes the occurrence of olivine and tridymite in lithophysæ in rhyolite and obsidian in the Yellowstone Park, as well as in some acid volcanic rocks from Lipari.<sup>20</sup> Penfield and Forbes<sup>21</sup> also found olivine in granite in Massachusetts. Olivine, as an orthosilicate, is unsaturated with respect to silica, and consequently a mixture of olivine and quartz under magmatic conditions would in general result in the formation of enstatite or hypersthene, according as the forsterite or fayalite molecule preponderated in the olivine. Under certain particular conditions, of course, magnesium or iron monoclinic pyroxenes or amphiboles might form. The glomeroporphyritic arrangement of the phenocrysts in the rocks under consideration precludes the action of magmatic vapours, as is postulated in the case of the obsidian lithophysæ.\* In these rocks the phenocrysts are of such dimensions and euhedral forms that they must have crystallised under plutonic conditions,<sup>22</sup> and at a time long anterior to the period of intrusion, as is shown by the resorption of the quartz. Hence, while it is impossible to tell whether the phenocrysts are merely porphyritic or truly xenocrystic, they may for all practical purposes be considered as the latter. The fact that the resorption is confined to the quartz shows that the holocrystalline portions have not been subjected to a high temperature, as, if they had, they would undoubtedly be dissolved, and such anomalous mixtures as quartz and olivine reprecipitated as pyroxene. It is significant that the crystal aggregates may be divided into two groups, one containing quartz, felspar, and pyroxene, and the other pyroxene, olivine, magnetite, and some felspar. Hence the two following possibilities regarding the origin of the olivine suggest themselves:—

(a) That the glomeroporphyritic aggregates are wholly or

<sup>19</sup> Am. Jour. Sci. (1885), 3rd ser., vol. 30, p. 58.

<sup>20</sup> Am. Jour. Sci. (1890), 3rd ser., vol. 40, p. 75.

<sup>21</sup> Am. Jour. Sci. (1896), 4th ser., vol. 1., p. 129.

\* See Note at end of Paper.

<sup>22</sup> cf. Judd, *Q.J.G.S.* (1890), xlvii., p. 380.

partly of xenolithic origin, and that the olivine originally crystallised from a basic magma which was subsequently inundated by siliceous material.

(b) That the formation of the olivine is analogous to that of magnetite in a granite.

Of these two, the first seems the more satisfactory, as the great chemical reactivity of the olivine, both in the molten state and in solution, militates against the second hypothesis, as does the fact that, with the exceptions mentioned above, olivine practically never occurs in granite. Again, most of the igneous rocks of the south end of Arran,<sup>23</sup> like those of Skye,<sup>24</sup> are undoubtedly of a hybrid nature, being formed of a granitic and a gabbro magma. Thus, the most probable conclusion is that the olivine-bearing parts of the rock are of xenolithic origin.

Occasionally the groundmass is doubly refracting as small spherulites occur, similar to those described by Harker<sup>25</sup> in the dyke at Wreck Bay, Rum.

The rock of which the pitchstone is probably a differentiation facies may be classed as a spherulitic quartz felsite, as it is composed of quartz and subordinate felspar in a base which has numerous spherulites with interstitial cryptocrystalline material. The material of the spherulites, which are perfectly ellipsoidal in shape, has a refractive index lower than that of quartz, and seems to be a mixture of felspar with large amounts of hydrated silica, probably of a hyalitic nature. The interstitial material sometimes develops granophyric structure, and numerous crystals of tridymite occur. These have now been replaced to a great extent by quartz, which develops owing to tridymite being a metastable modification of silica at ordinary temperatures. The spherulites are exceedingly well shaped, and probably in none of the other Arran pitchstones is such perfect development found.

#### PITCHSTONE AND FELSITE.

Since the only rocks which are found in the intrusions which we have considered are pitchstone and felsite, an examination

<sup>23</sup> Geol., North Arran.

<sup>24</sup> Tert. Ig. Rocks, Skye, pp. 169-197.

<sup>25</sup> Geol., Small Isles, p. 179.

of the genetic relations of the two types will probably assist in the interpretation of the composite nature of the dykes and sills. That little can be learned from the chemical analyses is shown by a consideration of the following table,<sup>26</sup> in which the numbers represent the lower and upper limits of the percentages of the various constituents of the two rocks:—

	<i>Pitchstone.</i>	<i>Felsite.</i>
SiO <sub>2</sub>	65 - 80	60 - 81
Al <sub>2</sub> O <sub>3</sub>	·5 - 14	9 - 19
Fe <sub>2</sub> O <sub>3</sub>	tr. - 3·4	·4 - 3
FeO	tr. - 1·7	0 - 5
MgO	0 - ·3	0 - 3
CaO	·5 - 2·5	0 - 4·5
Na <sub>2</sub> O	·3 - 5·5	·2 - 5·8
K <sub>2</sub> O	1 - 5·1	·3 - 7·1
H <sub>2</sub> O	·7 - 12·3	·7 - 5·2

The word “felsite” is used very loosely, and may designate any one of half a dozen types, such as devitrified pitchstone, quartz porphyry, ceratophyre, &c. These may be divided into two classes, those which arise through the devitrification of glasses and those which crystallise directly from the magma. Since a glass is merely a highly undercooled liquid, and therefore has a thermodynamic potential much higher than that of the crystalline phase, it is theoretically possible for all pitchstones to devitrify. That this is the case in Nature is proved by the rarity of glassy structures in palæozoic rocks. Various suggestions have been put forward to account for the difference in structure. Lagorio<sup>27</sup> believed that many glasses have approximately a eutectic composition, since this would involve the minimum melting point, and hence the maximum viscosity. Vogt<sup>28</sup> maintains that the presence of alumina has a similar effect, but Morozewicz,<sup>29</sup> on the other hand, starting from the physical-chemical law that an unsaturated solution will not readily deposit crystals, holds that a deficiency in alumina favours the formation of glasses. The primary things to be considered as effective in the process of cooling are temperature and pressure. Since Vogt has found that pressure has little direct effect on the solidification of

<sup>26</sup> Compiled from Prof. Paper No. 14 of U.S. Geol. Survey.

<sup>27</sup> *Tscher. Min. Mitt.* (1887), viii., p. 421 *et seq.*

<sup>28</sup> *Silikatschmelzlösungen.* Bd. 2.

<sup>29</sup> *Tscher. Min. Mitt.* (1898), xviii., pp. 1-20.

systems, such as quartz, orthoclase, albite, &c., we need only consider the temperature effects. Rapid cooling is in favour of the production of pitchstones, and so long as the rate of cooling exceeds the velocity of crystallisation glasses form. Again, acid magmas are generally highly viscous, and any conditions which entail the postponement of solidification to a low temperature likewise increase the viscosity. The two other factors which exert an influence in the same direction are the absence of mineralisers and the presence of an excess of soda in the magma. To sum up the main points, quick cooling and high viscosity, however induced, tend to favour the formation of glassy rocks, while slow cooling and low viscosity favour crystalline rocks.

In the case of the Glen Ashdale dyke the felsite may have crystallised as such during the process of cooling, since the spherulites are probably true ones, and Harker<sup>30</sup> has stated that true spherulites do not in general form as the result of devitrification. In this instance the best explanation seems to be that the felsite was intruded up the centre of a pitchstone dyke which had not completely cooled, and hence the centre rock underwent a comparatively gradual decrease of temperature, since the conductivity of a glass is fairly low, and the base solidified in a cryptocrystalline condition. Harker<sup>31</sup> describes the development of spherulites in a very similar rock at Boreraig, Skye.

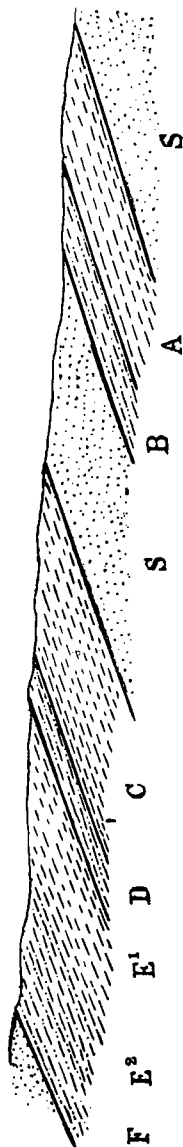
In the Monamore rocks, on the other hand, all the felsites are probably the result of devitrification. Structurally the rocks may be divided into two classes—A, C, E<sup>2</sup> are pitchstones; B, D, F are devitrified rocks; while E<sup>1</sup> may be considered as a transition form. Partial analyses have been made, and, while the whole sequence show several features in common, such as high alkali and low lime and magnesia content, they differ to some extent in the amounts of silica and alumina. The first group are all acid, and contain from 10 to 12 per cent. alumina and about 73 per cent. silica, while B and F are sub-acid, with 65 per cent. silica and 14 per cent. alumina. We have here a series of successive intrusions at very short intervals from the same magma, although, at the same time, some slight

<sup>30</sup> Geol., Small Isles, p. 181.

<sup>31</sup> Tert. Ig. Rocks, Skye, p. 281; also pl. xxii., fig. 1.

differentiation has taken place. While this undoubtedly had some influence in determining the amount of the devitrification, several other factors have been at work, as in E we have a gradual passage from an almost pure glass to a devitrified rock. The experiments of Bonney<sup>32</sup> show that a re-heated glass tends to crystallise very readily; further, that the presence of crystalline nuclei of the same molecular composition as the materials of the glass, and the existence of flow bands or other strain structures increase the tendency to devitrification. There is no doubt that the devitrified layers in these rocks occur along fluxion bands, while the areas round the phenocrysts were in a state of strain owing to the unequal contraction of the crystal and the glass during cooling. Daubrée<sup>33</sup> found that, if the re-heating were conducted in the presence of water vapour, crystallisation could be induced more easily, and he came to the conclusion that the presence of water, combined with the increase of pressure was the main factor. None of these rocks show the perlitic structure which is so characteristic in the

SECTION IN MONAMORE GLEN.



DESCRIPTION OF FIGURE.

S, sediments, 30 feet thick between sills; A, pitchstone, 20 feet; B, devitrified felsite, 10 feet; C, pitchstone, 25 feet; D, platy felsite, 4 feet; E¹ and E², spherulitic pitchstone, partly devitrified, 24 feet; F, devitrified rock, about 10 feet.

<sup>32</sup> *Q.J.G.S.*, 1885. Proc. p. 84.

<sup>33</sup> *Synthetische Stud. zur experimental Geologie*, 1880.



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Meissen and Hlinik<sup>34</sup> glasses, and which Allport<sup>35</sup> used to determine the original nature of the palæozoic Shropshire felsites. The Geological Survey describe a felsite from Glen Cloy<sup>36</sup> which shows ferruginous and chloritic decomposition products of the microlites, and this structure is taken to be evidence of devitrification. The presence of these developments in the rocks under consideration, as well as the general relationships and chemical composition of the series, tend to show that we have a number of successive intrusions, and that the felsites were the earlier products from the magma, the devitrification being due to the different chemical composition, the re-heating and changes in pressure due to the subsequent intrusions, and finally the probably greater content of water and other mineralisers.

It has been assumed hitherto that the microlites of the majority of the Arran pitchstones<sup>37</sup> are hornblende, although in Skye Harker<sup>38</sup> notes the exceptional occurrence of augites. Where simple belonites develop, the optical properties can often be determined, and hence the mineral identified, as in the case of the pyroxene crystallites of Glen Ashdale and the hornblendes of many of the Skye rocks.<sup>39</sup> It has been argued that the presence of augite phenocrysts favours the pyroxenic nature of the microlites. The relationships between hornblende and pyroxene, however, show that the co-existence in one rock of the two modifications of similar chemical composition is not incompatible with a comparatively simple cooling process. Consideration of equilibrium curves shows that a melt which would deposit pyroxene crystals under certain conditions would, under other conditions of temperature and pressure, deposit hornblende. The latter is the low temperature modification, while pyroxenes form at high temperatures and tend to pass into hornblende as the temperature falls, though the transformation is very

<sup>34</sup> A. Sauer. *Zeit. deut. geol. Ges.* 1888, xl., p. 601 *et seq.* O. Stutzer. *Monatsb. deut. geol. Ges.* 1910, pp. 102-113, pp. 205-214.

<sup>35</sup> *Q. G. J. S.* (1877), xxxiii., pp. 449-460.

<sup>36</sup> North Arran Memoir, p. 126.

<sup>37</sup> Allport, *loc. cit.*, and *Geol. Mag.* (1881), p. 438. Zirkel, *loc. cit.* Judd, *loc. cit.*

<sup>38</sup> *Tert. Ig. Rocks, Skye*, p. 406.

<sup>39</sup> *Tert. Ig. Rocks, Skye*, p. 403 *et seq.*

readily inhibited and difficult to effect. While the phenocrysts in these rocks formed under plutonic conditions, the formation of the microlites took place anterior to the final cooling, as is proved by the presence of a fluxional arrangement and the clear glass round the microlites, which shows that diffusion was still possible. As pitchstones may be assumed to have undergone a rapid fall in temperature and pressure in the process of solidification, the microlites develop immediately antecedent to, or very early in, this cooling process, while the much smaller longulitic growths arise in the later stages of cooling, perhaps when the rock was in the labile condition, when they would originate from lately formed globulites, which are to be regarded as minute spherical drops of supersaturated solution, and as essentially not crystalline.<sup>40</sup> Hence the nature of the microlites would depend on the particular temperature and pressure at the time of formation, and also on the degree of supersaturation of the magma with respect to the femic silicates under these conditions.

The complicated arborescent and plumose structures belong to the same generation as the belonites, and are merely skeletal developments of these. The three factors which favour the growth of skeletal forms are the rapid evaporation of solvent, viscosity, and low degree of concentration or solubility.<sup>41</sup> In the case of rock magmas the first of these may be neglected. Since the rate of growth at any point varies as the concentration gradient in the immediate neighbourhood, it follows that in a solution of high viscosity cooling rapidly skeletal forms must develop, owing to the velocity of crystallisation tending to exceed the rate of diffusion. The second and third factors mentioned above have the effect of hindering diffusion, and their operation is well exemplified in the pitchstones of the Sgurr of Eig<sup>42</sup> and Oigh-sgeir and of Monamhor Glen respectively. In the latter case we have a small quantity of femic material dissolved in a solvent mixture of quartz and felspar molecules. The degree of supersaturation necessary for the crystallisation of the femic silicates is only reached when the magma is viscous,

<sup>40</sup> Vogelsang. Die Krystalliten.

<sup>41</sup> Vogelsang, *loc. cit.*

<sup>42</sup> Geol., Small Isles, p. 179.

and the low concentration and high viscosity, combined with the great velocity of crystallisation, prevent the filling in of the spaces between the axes, and the result is a skeletal growth. The determination of the mineralogical nature of these fern structures is exceedingly difficult, though many of the Arran ones appear to give straight extinction. The globulites from which these structures arise must be assumed to have a certain crystallising force, which varies for different directions. Vogel-sang has termed the directions of greatest attraction the maximal axes, and the main axis of a crystallite is usually one of these. Since these, however, are not necessarily coincident with the crystallographic axes, optical constants determined with reference to them are of little value. In this connection Corstorphine<sup>43</sup> applied an ingenious chemical method, and proved the An Sloc microlites to be hornblende. It seems very probable that a similar conclusion would be reached in the other cases.

With regard to the existence of the "hyalitic" areas round the quartz phenocrysts, the identification of the fibrous material as hyalite and the intermediate layer as tridymite is due to Judd,<sup>44</sup> but he offered no explanation of the phenomena. While this development is certainly later than that of the phenocrysts and of the larger microlites, it is probably antecedent to the formation of the longulites, and thus took place during the process of cooling. In most cases the material has been derived from the surrounding glass, and not from the phenocryst, as the latter has usually perfect outlines, and has not suffered corrosion, which would result in rounded angles owing to the different solution pressure on different faces. The question of the tridymite further complicates matters. According to the researches of Day and Shepherd,<sup>45</sup> silica appears in about six modifications, and of these tridymite, in its two forms, is stable above 800 degs. C. The fact that many of the microlites in these rocks are hornblende, as well as the comparatively late development of the tridymite, would indicate that other conditions for the formation of the latter must be sought. Konigs-berger and Müller<sup>46</sup> ascertained the effect of heating obsidian with water under different conditions of pressure, &c. By an

<sup>43</sup> *Loc. cit.*

<sup>44</sup> *Q. J. G. S.* (1893), xlix., p. 550.

<sup>45</sup> *Am. Jour. Sci.*, 4th ser. (1906), xxvi., pp. 265-301.

<sup>46</sup> *Cent. für Min.* (1906), p. 663, p. 735.

ingenious filtering arrangement they found that at 360 degs. the rock decomposed and quartz and opal separated from the solution, while tridymite was formed in the undissolved residue. Quensel<sup>47</sup> concludes that opal and hyalite are the modifications of silica stable at low temperatures in the presence of water, and that the equilibrium between quartz and tridymite is greatly affected by the presence of co-solutes. On the other hand, Leitmeier<sup>48</sup> considers opal to be a gel of inconstant composition and varying properties, and quartz and chalcedony to be intrinsically the same. Lately phase diagrams have been worked out for silica, but, unfortunately, the only forms included are glass, quartz, and cristobalite,<sup>49</sup> and hence the conclusions are not applicable to complexes containing tridymite and hydrated modifications. Chrustschoff,<sup>50</sup> using a mixture of silica and a solution of hydrofluoboric acid, obtained cristobalite at 180-230 degs. C., quartz at 240-300 degs. C., and tridymite at 310-360 degs. There is no doubt that the occurrence of tridymite in the hyalite areas, as well as interstitially in the Burican felsite, is to be explained partly by the presence of co-solutes, such as water, and partly by the fact that the formation of tridymite involves a smaller diminution in volume than the formation of quartz.<sup>51</sup> As the former mineral is metastable at ordinary temperatures, it is finally transformed to the more stable quartz. Owing to the diffusion of silica to the pre-existing quartz crystals, the magma in the immediate neighbourhood must have been enriched in silica and water, and it is easy to understand how, on cooling, the water originally dissolved in the molten silica should become colloiddally absorbed in the hyalite gel. Any complete explanation of the formation of the single layer of tridymite, however, is impossible until the equilibrium of the system silica water has been thoroughly investigated.

In conclusion, I wish to express my great indebtedness to Mr. G. W. Tyrrell for his kindness in lending me his specimens and field notes, as well as for much assistance in many other ways.

<sup>47</sup> *Cent. für Min.* (1906), p. 370.

<sup>48</sup> *Cent. für Min.* (1908), p. 637.

<sup>49</sup> Smuts and Endell. *Zeit. für anorg. Chem.* (1913), 80, pp. 176-184.

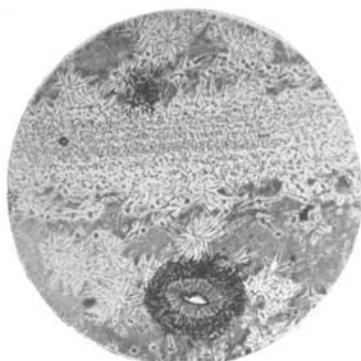
<sup>50</sup> *Neues Jahrb. für Min.* (1897), p. 1, p. 240.

<sup>51</sup> Endell and Rieke. *Zeit. für anorg. Chem.* (1912), 79, pp. 239-259.

NOTE TO P. 13.—The idea that the formation of orthosilicates in the presence of free silica may be due to the hydrolitic effect of hydrogen at high temperatures does not seem valid here in view of the absence of small olivines, while the "xenocrystic" theory is aided by the fact that the crystals are much corroded and somewhat uniform in size. Hydrolitic action between water and silica, however, may explain the small crystals of fayalite.

#### DESCRIPTION OF PLATES.

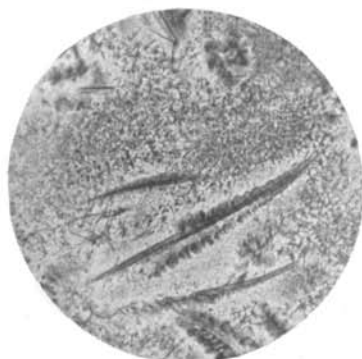
- Plate III., Fig. 1.—Base of 2nd sill, Monamore Glen. Shows the banded structure described on page 18, and spherulitic development of crystalline material round the partly resorbed crystal of felspar.  $\times 25$ .
- „ Fig. 2.—Composite plumose microlite as described on page 18.  $\times 125$ .
- „ Fig. 3.—Single arborescent microlite as described on page 18.  $\times 125$ .
- „ Fig. 4.—Axiolite with longulitic groundmass.  $\times 125$ .
- „ Fig. 5.—Pitchstone, 1st Monamore sill. Crystals of felspar surrounded by partly devitrified band (dark area) with isotropic base beyond.  $\times 30$ .
- „ Fig. 6.—Banded pitchstone, 2nd Monamore sill. Shows isotropic glass with microlites and line of minute pyroxene crystals along a flow-band.  $\times 30$ .
- Plate IV., Fig. 7.—Woollen Mill pitchstone, Monamore Glen. Continuous band of spherulites along a joint-plane (or flowband) with isotropic base on each side.  $\times 30$ .
- „ Fig. 8.—Woollen Mill pitchstone, Monamore Glen. Ring of spherulites round a plagioclase crystal.  $\times 30$ .
- „ Fig. 9.—Glen Ashdale dyke, western margin. Shows glomeroporphyritic arrangement of phenocrysts of quartz, oligoclase, and augite, with trace of perlitic structure and small belonites with "court of crystallisation."  $\times 15$ .
- „ Fig. 10.—Glen Ashdale dyke, eastern margin. Shows fluxion arrangement of pyroxenic belonites.  $\times 15$ .
- „ Fig. 11.—Pitchstone-porphyry, Loch na Leirg. Plagioclase crystals with orientated inclusions and hyalite areas round the margins; the dark crystals are augite.  $\times 15$ .
- „ Fig. 12.—Spherulitic quartz-felsite, interior of Glen Ashdale dyke. Crystals of quartz surrounded by double band of dark fibres of siliceous material in cryptocrystalline base.  $\times 30$ .



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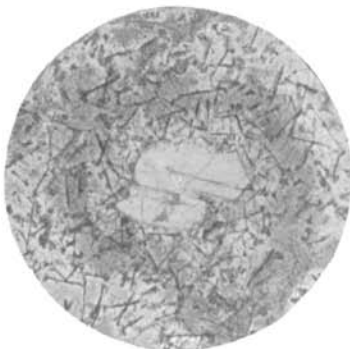
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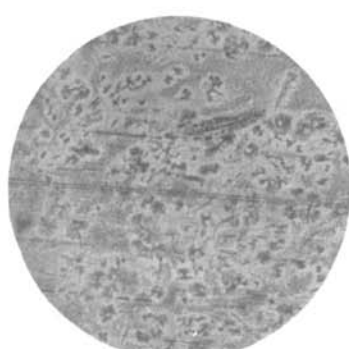
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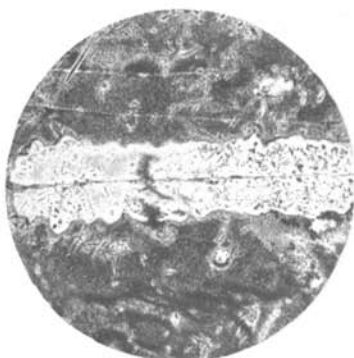


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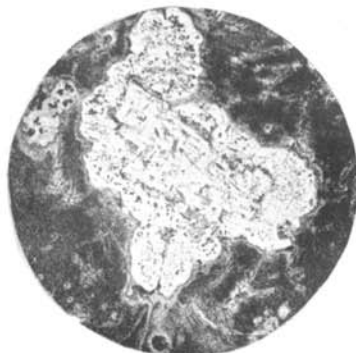
Photomicrographs of Pitchstones.

Trans. Geol. Soc. of Glasgow.

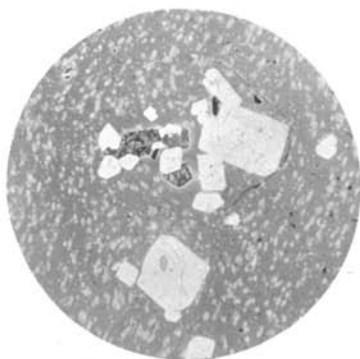
Vol. XV., Plate IV.



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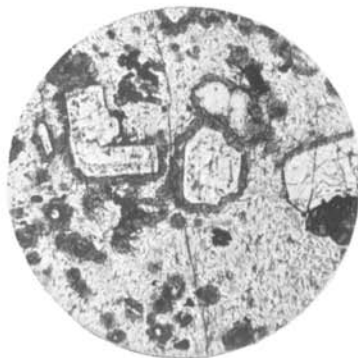
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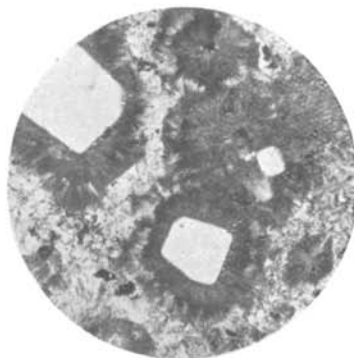
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Photomicrographs of Pitchstones.