Cataclastic pegmatites and calc-silicate skarns near Bunbeg, Co. Donegal.

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Introduction and general field relations.

In this paper is described a series of three small pegmatite dikes and the skarns produced by them in Dalradian calc-silicate hornfelses, and after full discussion certain conclusions are deduced as to the mode of origin of these rocks. This suite has not been described previously and lies to the south of Bunbeg quay and to the east of Loughlin island (fig. 1). The only published accounts of the area contain but passing reference to some of the features here described. In 1891 Nolan (1) merely noted the existence of 'remarkable beds of garnetiferous limestone with tremolite' near the small village of Bunbeg, whilst Zealley (2) in 1909 briefly referred to these hornfelses.

The hornfelses form part of an 'island' of pelites, hornfelses, and epidiorites which in plan is completely encompassed by the Donegal granodiorite, so as to appear to be what many geologists would call a roof pendant. The dikes to be described appear to trend east–west, and are seen in a vertical cliff immediately to the east of the southern point of Loughlin island (fig. 1). Both the strike of the metamorphic rocks and the lineation of the granodiorite (as determined by the preferred orientation of the felspars) are sensibly north–south (3). Unfortunately it is not possible to correlate these hornfelses with any others in the area. The limestone of Lough Anure described by Pitcher (4) is an analogous 'island' 4 miles SSE. of Bunbeg, and is one of several similar masses which are 'certainly structurally related to one another' (4, p. 126), and occur along a NW. line. The Bunbeg calc-silicate hornfelses cannot be justifiably correlated with these masses, being over $2\frac{1}{4}$ miles to the NE. of this line, and being separated from them by granite. The only other metamorphic rocks in the vicinity are massive quartzites occurring $1\frac{1}{2}$ miles to the east.

Field relations.

The hornfelses.

In a 21-foot high cliff along the western side of the tidal inlet immediately to the east of Loughlin island is an excellent exposure of the varied calc-silicate hornfelses dipping 75° E. of N. at 45°. The bedding is clearly picked out by compositional variation giving distinct bands of grossular and idocrase set in a white to blue-green matrix composed

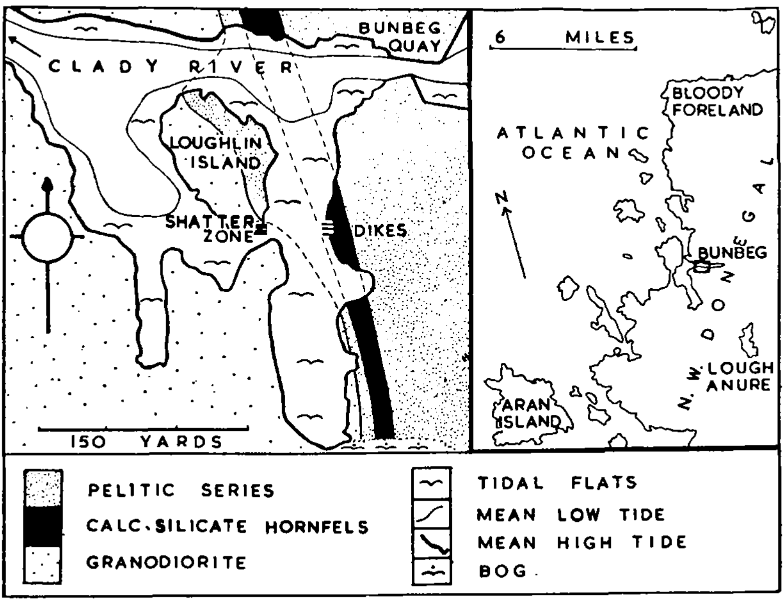

Fig. 1. Sketch-map showing location and geology of the Bunbeg area, Co. Donegal.

primarily of diopsidic pyroxene, wollastonite, and calcite. These minerals can usually be determined macroscopically. The formation, however, is by no means uniform, there being a general tendency to pass from a definite banded rock at the base of the exposure up into a more massive hornfels. Throughout the whole series there are isolated rhombic dodecahedra of garnet intergrown with idocrase, whilst in the lower part of the cliff-section besides these aggregates the bedding planes are picked out by bands, often 2 inches thick, of almost solid garnet and idocrase. In both cases there is an intimate intergrowth of these two minerals, and in the former case the idocrase actually occurs within the crystal boundary of the garnet. The higher, more massive pale greeny-blue rock only contains the euhedral garnets (or garnet-idocrase intergrowths) scattered randomly through it, whilst wollastonite needles appear lying in the bedding planes at most horizons.

The hornfels has apparently been stretched along a north south axis, as in the lower part of the exposure the more competent garnet-idocrase 'beds' have developed small boudinage structures, and the adjacent hornfels clearly shows compensational flowage (see fig. 2), and other internal plastic flow-structures occur at the same horizon.

FIG. 2. Boudinage structure developed in a competent garnet-idocrase band in the calc-silicate hornfels. The less competent bands, rich in calcite, diopside, and wollastonite, are seen to have effected compensational flowage. $\times \frac{1}{2}$.

The pegmatites.

There are three principal dike-like masses to be seen in the cliff, but observation is limited to two dimensions, which renders interpretation difficult. It is thought that these composite pegmatite dikes represent two phases of intrusion (distinguished in the subsequent text and in fig. 3 as I and II) and that their structure has been complicated by a complex cooling history which induced a zonal arrangement in the rocks of the second intrusive phase (II). Thus in the largest and most northerly dike, $4\frac{1}{4}$ feet wide at the base of the outcrop and tapering upwards a few inches, the sequence shown in table I can be detected. The spatial relations of the rock-types are indicated in fig. 3. It can be seen that the second intrusion was emplaced on either side of the initial pegmatite. The zonal arrangement is most clearly seen on the south flank of the dike, whilst on the north flank general decomposition, rotting, and crushing obscure the contacts.

This time-sequence between the two intrusive phases (I and II) is maintained because irregular stringers penetrate into the central material of the first intrusion (I), and also a xenolith of the latter is incorporated within the coarser medium-grained pegmatite of the second intrusive phase (II*c*). These relations are schematically illustrated in fig. 3B.

The second intrusion (II), where it is in contact with the hornfelses, has developed dark reaction zones varying in width from about ¼ inch to nearly 2 inches. The hornfelses have been differentially transformed,

TABLE I. The order of intrusion and consolidation illustrated in the largest pegmatitic dike.

Intrusion.	Description.	Grain-size.*
I	Diopside-microcline-perthite-pegmatite	Fine
II	Crystallized to give successive zones as follows:	
II*a*	Contact skarn zone	Fine
II*b*	White felspathic zone	Fine
II*c*	Medium pegmatite zone	Medium
II*d*	Quartz zone or core	Medium

* Fine, < 1 inch; medium, 1–4 inches.

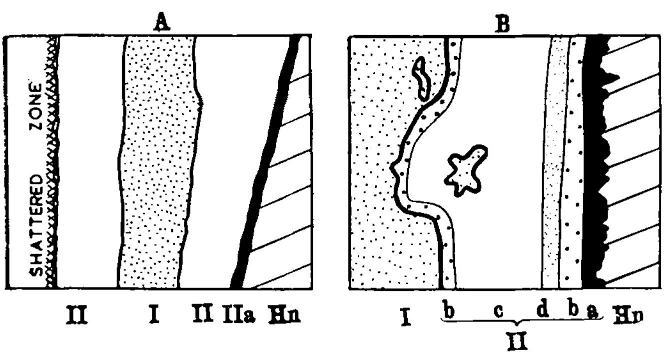

FIG. 3.

A. Diagrammatic cross-section of the largest dike.
B. Detailed section of the right-hand side of the same dike

Hn, Hornfels. I, First intrusion. II, second intrusion. II*a*, Contact skarn zone. II*b*, White felspathic zone. II*c*, Medium pegmatite zone. II*d*, Quartz zone.

as some of the more compact garnet-idocrase bands form small promontories projecting into the reaction skarn (II*a*). There is a sharp boundary between this reaction material and the cataclastic white felspathic zone (II*b*), but the latter blends into the central fine pegmatite of the first intrusion (I). It is postulated that, as shown in fig. 3B, the exposure shows a section across a sequence of successively precipitated zones of material deposited in a rudely concentric manner upon the then confining walls. Hence the material designated (II*b*) is considered to represent the first consolidation from the second magmatic intrusion. The medium pegmatite (II*c*) then consolidated, and the last fraction to solidify comprises the quartz zone (II*d*) representing the 'core' of the intrusion. As at present exposed the penultimate zone to consolidate, which is about 9 inches wide and contains felspars up to 3 inches in length set in quartz, is seen to be incomplete because the quartzose core (II*d*), which is $1\frac{1}{2}$–6 inches wide, has consolidated adjacent to the white felspathic pegmatite (II*b*).

The initial fine pegmatite (I) is of variable width (reaching $2\frac{1}{2}$ feet), and on the north side passes into medium textured pegmatite of the second (II) intrusion. Some 12–18 inches of the latter material is exposed, but as already stated the northerly extension is obscured.

This description applies to the largest of the three dikes, which is the only one reaching the base of the exposure. The other two are situated a few yards to the south, and both of these completely taper away downwards. They possess prominent reaction zones marginal to the milky white intrusive which simulates the white felspathic zone (II*b*) of the largest dike. Still farther to the south there is also a quartz vein, which, though sinuous, bears a dike-like relation to the hornfelses, and appears to have been to some extent differentially emplaced, etching out some of the bedding planes more than others. It is also sheathed in a minute reaction border, which varies 2–7 mm. in width and consists of wollastonite needles arranged parallel to the dike, except in the wider portions of the skarn where they assume a rudely radial orientation. Diopside crystals occur in interrupted thin bands along the skarn. The thin bands of diopside and clinozoisite of the *S*-planes (representing the original bedding planes) die away in the wollastonite-skarn, and it is probable that much of the pyroxenic material of the skarn has been produced from this primary material.

Microscopic characters.

The calc-silicate hornfelses.

As previously noted these rocks show a great deal of variation and are composed of varying amounts of dull red grossular, zoned brown idocrase, pale green diopside, wollastonite, calcite, quartz, and andesine. The proportion of calcite is the most variable; sometimes rocks with a gneissose appearance are composed dominantly of granular calcite (about 1 mm. in diameter) traversed by fine bands of diopside, intergrown grossular and idocrase, and occasional wollastonite (fig. 4). There is every variation in the amount of calcite present, so that these carbonate-rich bands contrast with those which are essentially grossular-

Fig. 4

Fig. 5

Fig. 4. Hornfels composed of calcite with small diopsides dispersed through it, and with the original bedding planes picked out by thin bands of idocrase (black) and grossular garnet (deep grey) which weather into prominent ridges on exposed surfaces. ×1·1.

Fig. 5. Hornfels showing abundant wollastonite (white) associated with quartz and diopside (pale grey), and porphyroblasts of aggregated garnet (deep grey) and idocrase (black). The subhedral porphyroblast is of the type referred to on page 744. ×1·3.

idocrase-rocks. These minerals are usually interspersed with diopside, andesine, and quartz. All the silicate minerals are more abundant along certain *S*-planes, whilst the idocrase is frequently elongated parallel to the *c*-axis, which tends to lie randomly in this plane. Likewise wollastonite is always acicular, with the needles in the *S*-planes. It varies from occurring as scattered needles to dense felted masses as shown in fig. 5.

It is thought that the quartz and andesine (Ab_6An_4 by Michel-Lévy method) have resulted from the introduction of exotic materials along the *S*-planes during the emplacement of the regional granite. Both minerals only rank as accessory constituents. Since this quartz is intimately associated with calcite, whilst wollastonite-bearing calcareous bands

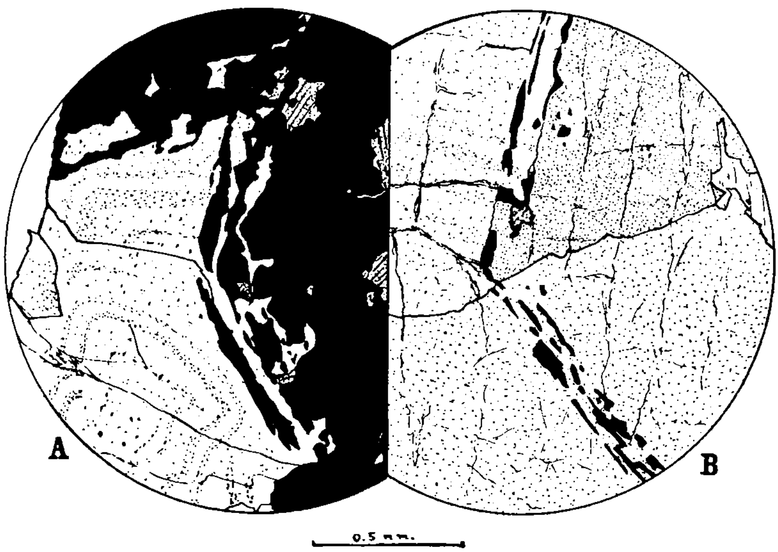

FIG. 6.

A. Hornfels showing differential replacement of garnet zones by zoned idocrase, representing an early stage in production of palimpsest structures. Diopside and quartz present in the garnet.

B. Palimpsest of euhedral grossular from hornfels which has been almost completely pseudomorphed by idocrase.

Crossed nicols. Garnet isotropic, idocrase stippled. ×20.

were produced in adjacent horizons by the initial metamorphism, subsequent metasomatism is indicated. This metasomatism has also effected diaphthoretic breakdown of grossular to idocrase in a manner similar to that described by Osborne in Carlingford (5). Contrary to the condition which so often exists, however, there is in these rocks no doubt whatsoever as to which mineral is being replaced. Thus, for example, within the limits of a single slide two excellent palimpsest euhedral grossulars were observed in differing states of replacement, as illustrated in fig. 6. The idocrase has obviously differentially picked out the zoning of the garnet. Such secondary idocrase frequently has better crystalline shape than the grossular, and often contains poikiloblastic clusters of garnet, giving a sieved appearance to thin sections. Further, the idocrase has grown about many of the diopsides contained in the *S*-planes without disturbing their positions, which is indicative of differential metasomatic growth of the secondary idocrase.

The grossular is sometimes massive, but more frequently occurs as subhedral to euhedral rhombic dodecahedra up to 1 inch in diameter (fig. 5). Mutual sieving commonly occurs between idocrase and the garnet, and in turn both are often highly sieved with diopside and a few grains of calcite. The poikiloblastic diopside occurs as rounded units normally with random distribution within the garnet, but occasionally a distinct linear band of similar grains may traverse an euhedral porphyroblast without having been deflected from the original *S*-planes by the growth of the grossular. This fact is considered to be of importance in connexion with the method of growth of porphyroblastic garnet in hornfels, as this example clearly shows that the developing crystal, although growing in a solid medium, did not express any facility to remove the 'unwanted' materials, neither was the enclosing hornfels deformed. Hence growth in the solid has not, in this case, necessitated the exercise of mechanical disruptive forces during crystallization. The previously described idocrase exhibits analogous relations. It is interesting in contrast to note that Osborne records 'certain garnet-rich rocks where the smaller wollastonite units have been pushed aside by the growth of the grossular crystals. . . . In such rocks the structure is porphyroblastic' (6, p. 294).

The pegmatites: the largest dike.

The mode of a representative sample of the first intrusion (I) is detailed in table II (column 1). The frequently twinned euhedral diopside is a salitic mineral of the diopside-hedenbergite range, occurring as crystals with a maximum dimension of 3·3 mm. Uralitic marginal alteration and patchy replacement by calcite are frequent. The diopside is set in quadrille-twinned microcline and microcline vein- and patch-perthite areas reaching 6·5 mm. in diameter. Some of the quartz was a deuteric introduction, being brought in along inter-crystal boundaries, and frequently producing slightly bulbous replacements, at times resembling crypto-myrmekite. This late-stage quartz entering along fractures in the pyroxene has 'stoped' and floated fragments apart. The quartz, and sometimes the felspar, is riddled with strongly prismatic euhedral apatites.

Sphene, which is tinged with pink in thin section, is abundant and perfectly euhedral, in contrast with the anhedral fragments occurring in the skarn (II*a*). This rock would appear to be of the type styled 'sphene rock' by Scott (7) in SW. Donegal, a term endorsed by Scott, Griffith, and Haughton (8), and later referred to by Zealley (2). This name is completely inappropriate in view of the fact that despite the noteworthy abundance of sphene which is a feature of this rock, modally it comprises less than 2 %. The diopside-bearing pegmatites from near Ellon described by Read (9) appear to be very analogous rocks.

TABLE II. Modes calculated from micrometric measurements and expressed as volume %.

Minerals.	1.	2.	3.
Microcline and microcline-perthite ...	57·2	71·7	23·7
Plagioclase	2·7	3·2	65·2
Quartz	26·4	20·8	6·7
Diopside	12·6	4·3	—
Sphene	1·2	present	0·1
Clinozoisite	—	—	2·1
Calcite	—	—	0·2
Apatite	present	trace	—
Muscovite	trace	—	—
Biotite	trace	—	—
'Pyribole aggregate' (see page 747) ...	—	—	1·4
Colour index	13·8	4·5	3·8

1. Diopside microcline-perthite-pegmatite of first intrusion (I) into the largest dike.
2. Pegmatite of second intrusion (II*c*) from north flank of the largest dike.
3. Central pegmatitic material from the middle dike macroscopically similar to (II*b*) of the largest dike.

In the white felspathic zone of the second intrusive phase (II*b*) microcline vein-perthite is the dominant mineral, together with a considerable amount of quartz and diopside associated with some oligoclase and a little sphene (as large euhedral and anhedral grains). Swarms of minute apatite prisms are also present, occurring most abundantly in the quartz. A little deuteric albite occurs around some of the perthites, and is sometimes in optical continuity with the exsolved albite. The diopside is fresh. The quartz is highly strained, although the rock as a whole lacks evidence of cataclasis.

On the north flank of the largest dike occurs a somewhat fine-grained facies of the medium pegmatite zone (II*c*) whose mode is given in table II (column 2). The pink colour of the rock is given by the microcline film-perthite occurring as grains up to 2·6 5·0 mm. in diameter. The rock shows excellent cataclastic structures with disruption and strain of the felspars, and there are frequently very ragged boundaries between the quartz and felspar. Small gaps left between these larger crystals on intrusion have been filled by minute quartzose and felspathic blebs. Creasing and twisting of quartz grains is common. In fig. 7 a large sheared sphene is seen adjacent to a highly twisted and mechanically

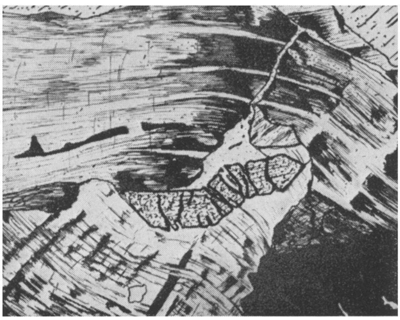

FIG. 7

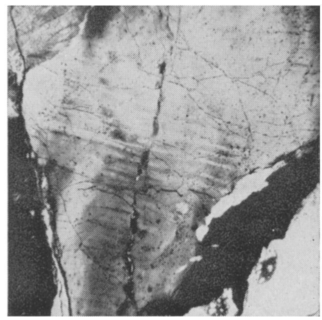

FIG. 8

FIG. 7. Creasing and twisting of quartz (above) and microcline (below), and disruption of a sphene (centre) as a result of cataclasis in the pink pegmatite (IIc) of the second intrusion into the largest dike. Crossed nicols. ×13.

FIG. 8. Photomicrograph showing unusual spindle-shaped strain-shadows in quartz produced during cataclasis of the pink pegmatite (IIc) of the second intrusion into the largest dike. Crossed nicols. ×30.

disrupted quartz. Cracks traversing both the quartz and adjacent felspar are filled with calcite. This stage of deformation was after some, but before other, quartz crystallization, because similar gashes are sometimes filled with quartz. Fig. 8 shows the effect of an unusual type of quartz straining. This has produced parallel spindle-shaped strain-shadows giving irregular partial extinction, which can only be likened to the appearance of the twinning characteristic of microcline, but occurring in only one direction. This, following the results obtained by Griggs and Bell (10), would seem to indicate deformation at relatively high temperatures, moderate pressure, and in the presence of solutions, which it is claimed creates a tendency to fracture quartz into needles with definite crystallographic dependencies. Such conditions would appear to be consistent with those giving rise to the metamorphism of the calc-silicate series.

The well-cleaved euhedral sphene crystals are up to 1·5 mm. long. Calcite in addition to forming the veins alluded to above, has almost completely pseudomorphed the diopsides. The felspars are considerably kaolinized.

The pegmatites: the two smaller dikes.

These two dikes are essentially similar and in both cases the central pegmatitic rock macroscopically simulates the white felspathic zone (II*b*) of the largest dike. A modal analysis of this rock from the middle dike is given in table II (column 3). More than 65 % of a well-zoned basic oligoclase (with excellent albite and pericline twinning) is present, occurring as crystals up to 9 mm. long. This plagioclase shows mortice-structure produced by cataclastic disruption, which gives uneven extinction. The microcline is slightly perthitic and poorly twinned. The uneven grain-size of the rock is due to late packing of the spaces between phenocrysts with smaller (0·1 mm.) grains of plagioclase and quartz. Clinozoisite is quite common, and crystalline calcite is often associated with it. Both these minerals occur interstitially and are bounded by rectilinear margins, taken to indicate late-stage or deuteric development, and since this calcite occasionally cuts through the epidote, the latter was probably solid before the calcite.

The modal 'pyribole aggregate' indicated in the mode is uralitized diopside, with traces of the pyroxene in the core, and in some cases clinozoisite is intimately intergrown with the uralite. Some of these complex masses show alteration to diffuse calcite.

The marginal facies of the middle dike adjacent to the skarn shows diopside-pegmatite with predominant microcline and some plagioclase and clinozoisite. A little replacive, and also some interstitial, calcite occurs together with a trace of fibrous muscovite (the latter having a rather 'zeolitic' habit). The diopside is uralitized marginally. Plagioclase is highly kaolinized, whilst the potash-felspar is fresh and sometimes has untwinned cores. Many of the large felspars have been mechanically disrupted giving anomalous extinction patterns probably due to cataclasis during magmatic intrusion with concomitant 'cementation' by a host of smaller crystals of quartz and felspar. The complex texture makes modal analysis difficult, but potash-felspar predominates considerably over plagioclase.

Contact skarns of the two smaller dikes.

The second pegmatitic intrusion (II) has produced a marked skarn at its contacts with the hornfels. The middle dike tapers downwards to such an extent that near its lowest extremity the intrusion becomes less than an inch wide, and the pegmatitic material therein comprises about 70 % felspar, there being nearly equal quantities of albite-oligoclase (about Ab_8An_2) and patch-perthite. All this felspar is shattered, with chlorite and calcite filling the ruptures. Quartz, after the felspars, is the next most abundant mineral and occurs as small grains. Both the 5–10 % of calcite and the small proportion of clinozoisite are thought to be primary in view of their straight line contacts and interstitial relations. A little zoned chalcedony exhibits analogous relations.

Cataclastic structure is not so marked in this rock, but mortice-structure in some of the felspars, and disparity in crystal size probably imply late cementation of the larger grains (which experienced slight cataclasis during intrusion of the magma) by smaller second generation crystals with grain-sizes ranging 0·30–0·07 mm. The latter are composed of quartz, lamellar-twinned plagioclase, some untwinned felspar (? K-felspar), together with calcite, clinozoisite, a little rather mushy muscovite, and occasional chalcedony.

In the contact zone there is copious very pale watery-green non-pleochroic diopside showing uralitized margins. Quartz is a little more abundant than in the pegmatite. Felspars (abundantly rich in apatite needles) are, being the finer in grain-size, packed between the pyroxenes. Calcite is quite prominent and occurs both as interstitial masses and also as regular-edged replacements in other minerals; frequently the felspars are almost completely replaced by calcite. Thus calcite has two habits; that which is interstitial, filling angular gaps between minerals, would appear to be primary, whilst the sprawling replacements of felspar, which are more prominent in the contact zone, appear to be of a metasomatic origin.

Contact skarn zone (IIa) of the largest dike.

This skarn may be divided into two distinct reaction zones:

(*a*) the 'black' zone adjacent to the white felspathic zone (II*b*), and

(*b*) the 'green' zone adjacent to the hornfels (Hn of fig. 3).

The white felspathic zone (II*b*) close to the 'black' zone contains plagioclase, quartz, and some microcline, all being highly cataclastic, whilst calcite, clinozoisite, sphene, and muscovite also occur. The plagioclase has a composition between oligoclase and andesine and occurs as grains up to 1·5–2·0 mm. diameter. Anhedral quartzes are sometimes more than 3 mm. long. The clinozoisite and calcite are mainly interstitial and are thus presumed to be primary, although part of the calcite and a little of the epidote has a nebulous replacive secondary aspect. Some muscovite is also interstitial.

The plagioclase shows marked cataclasis with prominent micro-shears and also distortion by cracking with opening of the cracks allowing entry of clinozoisite and calcite. It is considered that the latter two minerals are primary, as in the case of the Fen carbonatites described by Bowen (11 and 12). It is also noteworthy that according to Eskola (13) the Becket granite-gneiss of Massachusetts can contain 2 % of primary calcite, whilst von Eckermann in his latest work on the Alnö complex accepts the agency of magmatic carbonate (14, p. 99). Sometimes even the calcite appears to be slightly strained giving wavy extinction and twisted lamellae, and likewise some of the interstitial clinozoisite and muscovite is twisted to a limited extent, but none of these minerals has suffered disruption comparable with that manifest by the felspathic minerals.

In the 'black' zone of the skarn biotite and actinolite occur. The actinolite appears as fibrous masses $< 0{\cdot}6$ mm. long arranged in irregular clots along the contact. It has an absorption of $\gamma > \alpha$ (being pleochroic between bluish sap-green and very pale yellowish sap-green), and $\gamma{:}c$ about 16°. It shows an uralitic habit, sometimes sending fine fibrous masses into the surrounding minerals, and high-power examination shows small-scale alteration to calcite. The biotite occurs in two habits —either as small flakes, or alternatively as sub-radial interstitial material of 'zeolitic' habit, such as is frequently found in metasomatized aureoles. Along this contact, but just within the pegmatite, a few small ragged penninized grains of biotite are developed between disrupted felspars, and are often intimately associated with deuteric calcite as shown in fig. 9. The calcite illustrated is both interstitial and also somewhat replacive with respect to the felspars. The biotites in the skarn show effects of minor mechanical strain which occurred prior to the latest deuteric stage. Fig. 10A shows that mica has replaced anhedral cataclasized oligoclase (which is also calcitized), whilst its opened cleavages have been filled with quartz and possibly a little felspar. These features are reminiscent of the mica-lamprophyre of South Hill, St. Helier, Jersey (described by Searle, 15), in which magnesian carbonate has filled opened mica cleavages.

Sphene is abundant as minute broken or anhedral grains, frequently occurring in swarms. Subhedral diopside occurs sparingly adjacent to the pegmatite, and steadily increases in concentration towards the 'green' zone. Some quartz also occurs in this zone.

Towards the centre of the 'black' zone corroded fragments or palimpsests of silicates, particularly oligoclase occur within areas which have been completely calcitized, as illustrated in fig. 10B. Towards the 'green' zone small apatites become more abundant, and large sinuous quartz crystals also become common, being most abundant along the junction between the zones. The 'green' zone is narrower than the 'black', and is clearly transitional between the latter and the hornfelses. Biotite and sphene, common in the 'black' zone, now disappear, whilst diopside, quartz, and calcite become dominant, and anhedral isolated grossulars increase towards the hornfels. Diopsides of all sizes sieve the calcite, whilst the quartz was probably a late introduction. The resistant bands of hornfels which embay the skarn zone are composed of the usual idocrase-grossular assemblage with a little diopside and calcite.

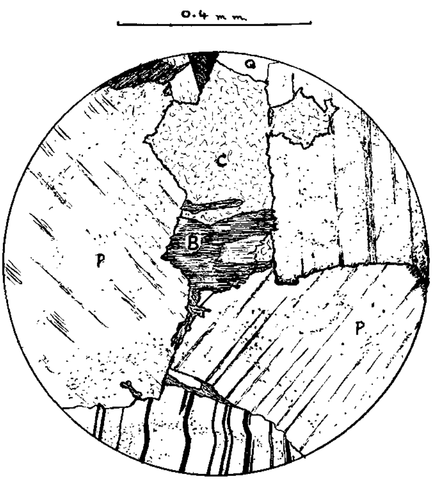

FIG. 9. Pegmatite (II*b*) marginal to the skarn of the largest dike, showing the intimate relationship between biotite (B) and deuteric calcite (C), and also the interstitial and replacive habits of calcite with respect to plagioclase (P). Quartz (Q) is also present. Crossed nicols. ×32.

Although these are the general features of this contact skarn, it should be recorded that near the top of the cliff the dike is considerably broader and consequently the effects of mechanical strain were less intense, and there is a slightly different assemblage. The effects of cataclasis on the felspars seems to be partially crystallographically healed and late-stage quartz has entered between the crystal boundaries, partially replacing the felspars. In the 'black' and 'green' zones relations are similar except that in the former actinolite and biotite are lacking, and in the latter quartz and felspar are more prominent so that a distinct light-coloured rim occurs round the garnet-idocrase promontories. Also the felspar in the skarn has been decomposed, but not so strongly calcitized as in the lower portions of the dike where cataclasis is more marked. Hence it appears that in this upper part late-stage (deuteric) action was curtailed restricting the formation of actinolite, biotite, and calcite, probably as a result of less easy access consequent upon poorer cataclasis. The introduction of quartz, however, has been intensified, both in the extreme marginal part of the dike and also in the outer part of the skarn.

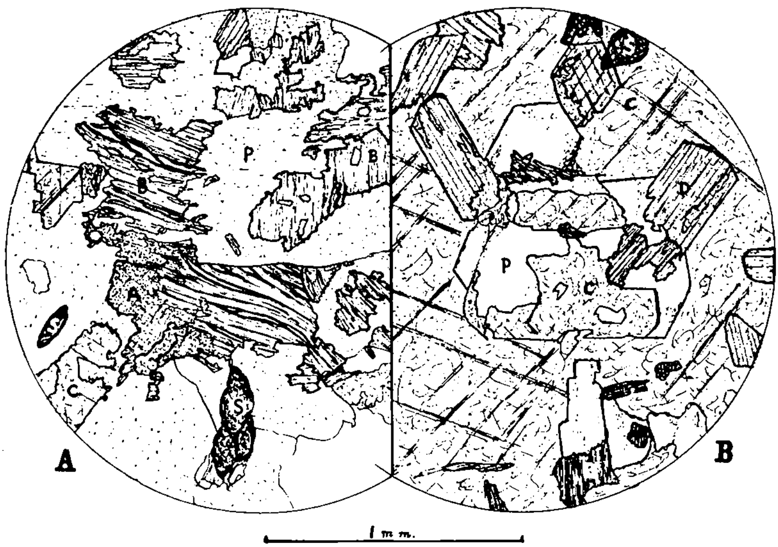

FIG. 10.

A. The association of plagioclase (P), calcite (C), biotite (B), actinolite and pennine (A), and sphene (S) in the contact skarn II*a* ('black' zone) of the largest dike. The biotite reflects minor mechanical strain which opened the cleavages allowing infilling with quartz.

B. Advanced calcitization of the 'black' zone skarn of the largest dike, showing active pseudomorphism of all the silicates. Note especially the marked replacement of the euhedral plagioclase in the centre of the field. Euhedral diopside (D) abundant. Plane polarized light. × 17.

INTRUSION SEQUENCE.

The production of skarn is thought to have been a composite process because of the dual intrusion. The initial intrusion assimilated hornfelsic materials, and this augmented magma produced the potassic pegmatite with nearly 13 % modal diopside (table II, column 1). The hornfels may have been completely dissolved prior to the pegmatite crystallization, or alternatively the diopside may simply have been recrystallized. Even the latter hypothesis implies a complete dissolving away of the enclosing hornfels, because the diopside always simulates a primary crystallization, a feature which is completely analogous to the diopside pegmatites near Ellon, where Read (9) attributes the crystalline perfection of the sphene and diopside to early crystallization from the contaminated pegmatite magma. Campbell Smith (16, p. 181) has suggested that the diopside-bearing veins at 'Marble Outcrop' and 'Marble Dike' in South Victoria Land are similar to these Donegal pegmatites, and in these Antarctic specimens which he described, it is suggested that very acid intrusions assimilated metamorphic limestones and granulites. Emmons and Calkins (17) also record diopside aplites with 7·75 % and 12·67 % normative diopside in respectively scapolite-poor and scapolite-rich dikes cutting the Madison limestone near Philipsburg, Montana. Also in the recent work of Hieke (18) and Schiavinato (19) strong support is given for endomorphic assimilation of limestone by acid plutonic masses (assisted by pneumatolytic-hydrothermal action), giving rise to pyroxene- and sphene-rich skarns.

It is interesting to note that Eskola (13) thinks that 'assimilation usually occurs where the intrusive rock shows banded structure and a high degree of protoclastic crushing and shearing, whilst it does not occur in masses which have been intruded and crystallized under quieter conditions . . .' In describing the Bazena region Schiavinato (19) has also noted the effects of dynamic pressure producing cataclasis in quartz, plagioclase, and calcite of the endomorphic zone.

The diopside-rich first intrusion (I) is only seen in the largest, most northerly dike. The rock-types designated and described as of the second intrusion (II) are all thought to have been part of a later intrusion into the two tapering dikes to the south and also on either flank of the first intrusion (I) in the largest dike. That is to imply that the various rock-types of the second intrusion all crystallized from a single magma and that successive shells or zones were precipitated on the perimeter of the magma cavity. This marked zonal arrangement appears to be in harmony with the recent hypothesis of Cameron, Jahns, McNaire, and Page (20) in which the authors suggest that zoned pegmatites form as a result of fractional crystallization of a single magma intrusion in such a way that successive crops of crystals are deposited against the walls until the chamber is filled. This hypothesis allows for such successive shells being complete or incomplete, due to lack of precipitation or reaction between crystals and rest-liquid. Reference to fig. 3B shows that in the Bunbeg dikes the medium pegmatite zone (II*c*) is incomplete, causing the core or quartz zone (II*d*) to be eccentric.

The fact that the two smaller dikes are narrower and tapering would, on this hypothesis, anticipate the fact that the central zones of the second intrusive phase are absent, whereas if a three-dimensional study were possible a more complete series might (and should) be revealed. There are, however, no outcrops immediately to the east of these exposures.

A point of difference exists between the numerous examples described by Cameron, Jahns, McNaire, and Page in their monograph (20) and the largest dike at Bunbeg in so far as in the latter there are two distinct phases of intrusion, whereas in the monograph it is implied that a single intrusion is usual in all pegmatites. A difficulty also arises in connexion with the hydrothermal quartz-vein which occurs farther to the south. The authors of the monograph in enunciating their theory give numerous examples of 'fracture fillings' which are described as being primarily quartzose, and cutting both the parent pegmatites and the country-rocks. It is here suggested that the quartz vein at Bunbeg is such a fracture filling, but the fact cannot be proved, though it seems reasonable to regard all four of these minor intrusions (the three pegmatitic dikes and the quartz vein) as penecontemporaneous and related.

Acceptance of this hypothesis implies that the skarns here described were produced during the second intrusive episode (II), and in this case there is ample evidence, in the cataclasis, of a forceful injection of a true magma (i.e. a mixture of liquid and solid phases), rather than for the existence of a 'pegmatitic thoroughfare' of the type postulated by Quirke and Kremers (21). The effects of cataclasis would not necessarily be preserved in the inner zones of the pegmatite, where slow cooling would allow 'healing' by recrystallization.

The original cavities into which the pegmatites were intruded were east-west minor shatter zones marginal to the Bunbeg 'island', and the continuation of such shatters is seen in, and has probably given rise to, the topographic gap between Loughlin island and the adjacent shore. It is noteworthy that at this point 3 % of modal muscovite occurs in the granite, whilst in neighbouring localities this mineral is too insignificant to figure in the mode. This granite also contains 45 % of quartz and far less plagioclase than adjoining granites.

Thus, although it must be admitted that some of the interpretations are possibly analogous to those styled 'anthropomorphic' by Perrin and Roubault (22), it is considered that these dikes have been produced essentially by forceful intrusion and concomitant deuteric and/or metasomatic action. This contention is maintained despite the fact that the normative felspar of the pegmatites whose modes are given in table II would undoubtedly, when plotted on an Or: Ab: An felspar ternary diagram, lie well astride, and away from, the cotectic line joining the Or: An and Ab: Or eutectic points as defined by Bowen (23). In describing some zoned pegmatites from the Black Hills of South Dakota, Higazy (24) has given strong arguments in favour of their production by reorganization of, and differentiation from, pelitic and semi-pelitic media. This concept is partly based upon the hypothesis that the rocks could not have a magmatic origin because the normative felspar lies well within the orthoclase field of the ternary diagram, that is, on the potash-rich side of Bowen's eutectic. Bearing in mind the nature of the enclosing hornfelses at Bunbeg it would seem reasonable to assert that they could not yield the requisite materials (particularly K and Na) to form the dikes, and also the other materials giving the acidification of the granite on Loughlin island. It is also considered to be highly unlikely that the pegmatites were 'produced' from the pelites stratigraphically higher or lower than the calc-silicate series, and then moved to their present location by rheomorphic processes. Hence the criteria used by Higazy would appear to be inapplicable to the cataclastic pegmatites under discussion, but, whilst claiming an essentially magmatic origin for these dikes, it should be recognized that it is unlikely that there is a unique solution to the problem of the genesis of pegmatites, and this paper has been written with a view to giving a contribution to the study of pegmatites rather than that of trying to enunciate dicta applicable to pegmatites in general.

The skarns.

Following from the argument above, the skarn bordering the latest intrusions has been produced by interaction between the second intrusion (II) and the hornfelses. There can have been no turbulence during the reaction because of the sharpness of the junction (excepting possibly in the widest portion of the largest dike); but a little mechanical deformation seems to have continued at all stages in the history. This, however, was only of a mild degree, as seen in the opening of the mica cleavages already described. The 'black' zone seems to have been produced by metasomatic introduction of hydrothermal materials, giving rise to plagioclase and quartz. Potash-felspar does not occur, but biotite is present in this narrow zone, and has probably developed instead of microcline under the influence of the hydrothermal activity; likewise actinolite occurs at the expense of diopside.

With regard to the calcite and clinozoisite, it is suggested that these are definitely either of deuteric or late-stage hydrothermal origin. In this regard it is noted that Bowen (11 and 12) does not think that carbonates could have crystallized from a magma, but that they occur in the Fen area as a replacement. In this area Bowen discussed differential calcite metasomatism, whereby microperthite is attacked first, and subsequently aegirine followed by hornblende.

This sequence of differential replacement has not been perfectly followed at Bunbeg. In the largest dike the calcitization has attacked the pyroxene but not the felspar to any great extent. In the reaction zone plagioclase has been altered most, and the pyriboles to a lesser extent, thus giving a close approximation to the examples described by Bowen. At the same time the replacement is undoubtedly guided by the deformation planes set up by the cataclasis. It must also be remembered that there is plenty of interstitial calcite and clinozoisite which would appear to be of at least deuteric origin, and although close similarities exist between these replacements and those described by Bowen, some of the calcite is definitely primary. Emerson (25, p. 19) records allanite-pegmatites and sphene-pegmatites replacing isolated tracts of limestone included in the Becket granite-gneiss. Their 'silicates are rich in calcium and suggest the capture by the heated solutions of a portion of the calcium from the limestone which was being dissolved to make place for the new rock. The rare elements suggest the deep-seated source of the hot solutions.' Eskola (13) also accepts the existence of primary calcite as previously mentioned, whilst von Eckermann (14) postulates a definite carbonate magma. A deuteric medium would appear to be necessitated to explain the late forming primary minerals associated with the present pegmatites and skarns. The deuteric origin of the calcite is further substantiated by the fact that some of the quartz was introduced at an even later stage.

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