GEOLOGY AND PETROLOGY OF SOME COMPOSITE AND MULTIPLE INTRUSIONS FROM ARRAN

and

SOME DYKE ROCKS FROM INISHOWEN, CO.DONEGAL, IRELAND.

T H E S I S

SUBMITTED TO THE UNIVERSITY OF GLASGOW

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

by

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CONTENTS

COMPARATIVE/

INTRODUCTION.

The investigation is a comparative study of the geology and petrology of some interesting composite and multiple intrusions from the Isle of Arran in the Firth of Clyde. The study includes a revision of Judd's famous work on the dykes of Tormore shore and Cir Mhor, and a detailed examination of the tholeiite--quartz-porphyry sill and dyke of Drumadoon (Buteshire, 6 inch Ordnance Survey sheets 253 N.E. and 248 S.E.), and the hypersthene-dolerite--quartz-porphyry intrusions of Bennan (Buteshire, 6 inch Ordnance Survey sheets 254 S.E. and 259 N.E.).

PREVIOUS RESEARCH.

These intrusions have been described in the past by various geologists among whom were Jameson and Ramsay. No modern work has appeared on the Tormore and Cir Mhor dykes except that of Judd who also includes a short study of the Drumadoon composite dyke at An Cumhann (1893, pp. 543-564). The first modern description of the Bennan intrusion is given by Corstorphine in his study of rocks from South Arran (1895, pp. 443-470). J.V.Harrison's paper is mainly a brief petrographic account of this intrusion (1925, pp. 173-183). In the Geological Survey Memoir on the Geology of Arran, G.W. Tyrrell gives short descriptions of all these intrusions and brings them up to date by including his own data (1928). In view of the scanty nature of our knowledge regarding these intrusions, this detailed comparative study was undertaken.

DYKES OF TORMORE SHORE AND CIR MHOR.

THE GREAT NORTH AND SOUTH DYKE.

(Judd's No.I dyke on Tormore Shore).

Judd's detailed description of this dyke was confirmed by the present mapping (Plate XI, b. Fig. 1). The dyke shows numerous variations in hade and at its northern extremity it is a vertical body, whereas in the south it has a hade of at least 60 degrees. It is mainly composed of pitchstone which is banded parallel to the walls of the intrusion and at the southern extremity is intermittently flanked by a similarly banded felsite which is, however, completely absent near the high-water mark.

On the eastern margin of the southern end of the dyke, Judd noted a band of 'augite-andesite.' A similar band has also been observed by the author on the western side. Both the bands can be traced from low-water mark to about high-water mark beyond which they cannot be followed. Judd records that the eastern band is later than the pitchstone. The author found that both the bands chill against either the felsite or the pitchstone and hence they are later than the pitchstone.

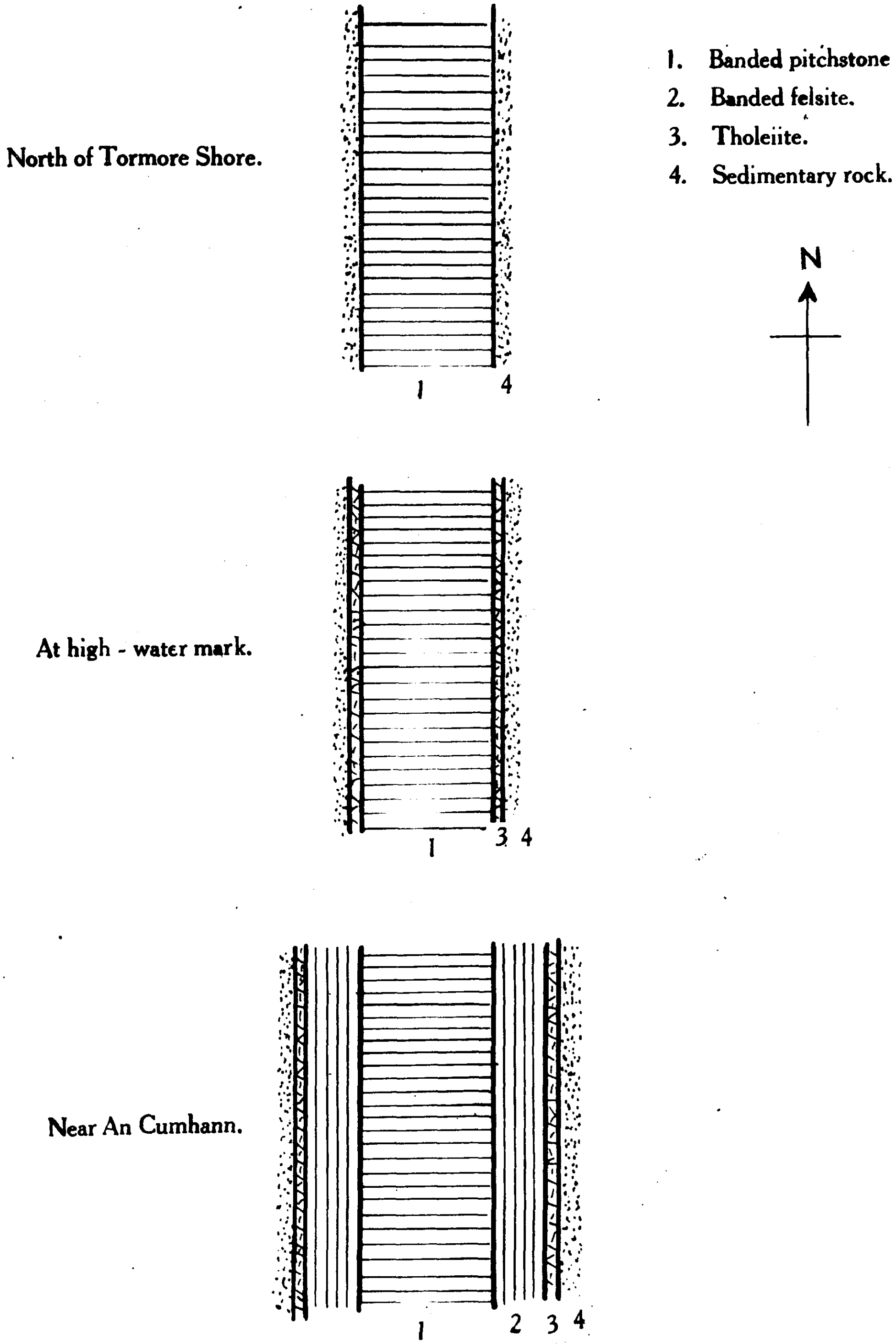
PETROGRAPHY.

Pitchstone:(Specific gravity: 2.343). The rock is green, distinctly banded, composed of alternating layers of greenish and/

Fig. 1. The great North - South dyke, Tormore shore.

(JUDD'S No. 1)

NOT TO SCALE



and yellowish glassy material. In thin section the rock shows numerous features characteristic of pitchstones as described by Harker (Tyrrell, 1928, pp. 224-5). It is microporphyritic with corroded phenocrysts of quartz and basic oligoclase, some of which show peculiar twinning. The felspars often enclose sparing anhedral grains of pale yellow augite intimately associated with iron-ore, the latter also occurring separately. Some grains of iron-ore are associated with euhedral apatite and zircon. The rock has a glassy base with numerous crystallites and microlites. The crystallites are all pleochroic from pale brown to dark green with an extinction angle of 17^{o}, and are hornblende. The microlites show fern-like and arborescent growths. There are a number of spherulites composed of radiating alkali-felspar and crystallites of hornblende, besides many drusy cavities filled with irregular grains of quartz. The banding of the rock is related to the unequal distribution of crystallites as described in the Arran memoir (op.cit., p.226), and well seen in the Geological Survey slides (5656, 5657).

Felsite: (Specific gravity: 2.538; this value is higher than that for the pitchstone). The rock is greyish, vitreous and banded similar to the pitchstone. One handspecimen shows a passage between the pitchstone and the felsite. In thin section the/

the felsite shows a few microphenocrysts of altered felspar in a groundmass composed mainly of micropegmatite and spherulites. Numerous needle-like pseudomorphs of a mafic mineral can be recognised. The similarity of the banding, the transition noticed in handspecimen, and the occurrence in the two rocks of mafic pseudomorphs, suggest an intimate relationship between the types; according to Judd the felsite is a devitrified form of the pitchstone.

Tholeiite: (Specific gravity: 2.726). Megascopically the rock is dark grey and medium-grained with numerous pyroxene grains. No xenocrysts or phenocrysts can be recognised. In thin section the rock is mostly composed of titanaugite, pleochroic from lilac-brown to pale yellowish brown; many of the grains are subophitic and ophitic with laths of plagioclase (Plate VI, fig.1). The plagioclase felspar occurs as irregular plates and prisms of various sizes, mostly multiple-twinned, with a refractive index higher than that of Canada balsam and having a maximum extinction angle of 37° (acid to mid labradorite). Iron-ore occurs visibly only in small quantity but presumably it is extensively present occult in the dark green glassy mesostasis, a feature common to tholeiites. There are some ocelli-like areas, consisting of felspar microlites, skeletal iron-ore and occasionally, fibrous serpentine.

NATURE OF THE DYKE.

Judd has described this as an "interesting example" of a composite dyke, which according to him is one "filled with materials differing from one another in chemical or mineralogical constitution." (op.cit., p.536). At this stage, the modern terminology regarding composite and multiple intrusions may be reviewed. Daly (1933, p.91) and Tyrrell (1940, p.31) lay emphasis on the contrast in chemical composition among the components. According to them, multiple intrusions are uniform in composition throughout the complex, whereas composite intrusions are due to "successive injections of different melts." (Daly). Others like Thomas and Bailey (1924, p.32), Tomkeieff and Marshall (1935, p.239) and Haff (1941, pp.839,852), emphasise that the more important factor is the time interval between successive intrusions, as judged by the presence or absence of chilling of one member against another. The present trend of petrologic thought may be summarised as follows (also see p. 68 of this paper): (1) composite intrusions are composed of parts of recognisably different composition, (2) as a complex they chill exteriorly against the country rock, (3) the component parts do not chill against one another. (Mull Memoir, 1924, p.32), whereas "multiple intrusions... consist of several members in parallel arrangement, each member being/

being chilled against one another or its associates," (Ardnamurchan Memoir, 1930, p.63). According to this definition, Judd's No. I dyke must be classified as a multiple dyke since the tholeiite is chilled against either the felsite or the pitchstone.

THE NORTHERN TRANSVERSE DYKE.

(Judd's No. II dyke on Tormore Shore).

Comparison of the field plans of this dyke both by Judd (op.cit., p.555) and the author (Plate XI and Fig.2), reveal important differences in the outcrop of the 'pitchstone-porphyry' which, according to Judd, forms a part of the felsite sometimes and at other times intersects the adjoining masses of "andesite." (op.cit., p.555). The author found that the pitchstone occurs only between the felsite and the southern tholeiite apparently pinching out in the cliffs to the east and nowhere in the exposures studied, crosses the felsite. The tholeiite occurs on both sides of the felsite and is chilled only against the sandstone but not against either the pitchstone in the south or the felsite in the north. Hence, it is concluded that the tholeiite is earlier than the associated rocks of the dyke-complex. To the north, there is a thin 1½ ft. dyke of dolerite hading due south and joining the composite dyke at an angle in the sea.

PETROGRAPHY/

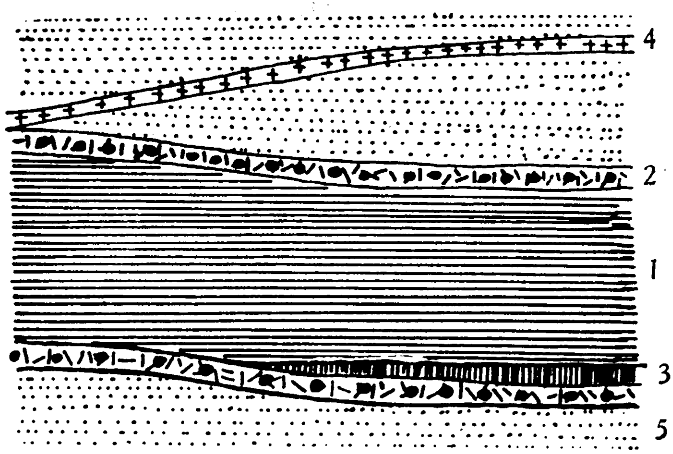
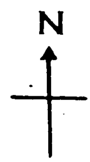


Fig. 2. The Northern transverse composite dyke.
(JUDD'S No. 11)

NOT TO SCALE

1. Quartz - felsite.
2. Tholeiite (xenoporphyritic)
3. Pitchstone
4. Coarse - dolerite dyke.
5. Sedimentary rock.



PETROGRAPHY.

Tholeiite: (Specific gravity: 2.789). It is a dark grey, fine-grained rock, much lighter in colour and less coarse than the basic member of Judd's No. I dyke. Microscopically (Plate VI, fig.2) it is comparable to the Brunton type of tholeiite described from Mull (Memoir, p.312), though showing some significant differences such as the presence of xenocrysts of quartz and felspar. It is composed of granular augite (maximum extinction angle 44°), a few grains of which can be described as phenocrysts. There are many prisms and plates of acid labradorite (maximum extinction angle 30°); some grains occur also as microphenocrysts, a few of which (T.17) show dark inclusions. Section T.17 (southern tholeiite) shows two grains of ortho-pyroxene slightly pleochroic from pale pink to pale green and having straight extinction; the grains show alteration along cracks to serpentine. Iron-ore occurs quite abundantly, mostly as irregular grains. The base of the rock is composed of cryptocrystalline or almost isotropic matter occurring interstitially, associated sometimes with a few grains of quartz. Needles of apatite are numerous.

Thin sections from both the basic members show xenocrysts. Felspar xenocrysts show abundant evidence of corrosion. They have interiors of granular or pitted appearance, which/

which show minute irregular grains of augite and skeletal iron-ore. Sometimes the groundmass invades part of the xenocryst. Most of the grains have a rim of fresh felspar high in relief and similar to the felspar of the rock (also recorded by Judd, op.cit., p. 547). Where the corrosion has not proceeded very far, the crystals show cores of original felspar with low extinction angle characteristic of mid oligoclase; they show numerous cracks probably resulting from expansion due to heat.

Xenocrysts of quartz with the characteristic rims of granular augite are present. Sometimes a number of apatite needles project into the quartz xenocrysts from outside. Many of the granular aggregates of augite seen in the section probably represent completely resorbed quartz xenocrysts. Comparison of the xenocrysts of quartz and felspar with the phenocrysts of the quartz-felsite show similarity in size and also in their granophyric inclusions, features which suggest a possible relationship.

The sections show drusy cavities filled with carbonate and secondary quartz surrounded by the cryptocrystalline base, skeletal iron-ore etc., and in one of them there are acicular needles of apatite.

Quartz-felsite: (Specific gravity: 2.510). This is the acid component of the composite dyke and is of much greater volume than/

than the basic member. It is a pinkish grey rock, the colour being due to iron-staining, with small macrophenocrysts of quartz and felspar set in a compact groundmass. In thin section (Plate VI, Fig.3), the rock is porphyritic with phenocrysts of corroded quartz and mid or basic oligoclase; the latter has an extinction angle of 12° and its R.I. is higher than that of Canada balsam and the crystals often enclose big needles of apatite such as are also found in the phenocrysts of pitchstones. The oligoclase crystals occur in groups and with the quartz are set in granophyric groundmass composed of comparatively coarse intergrowths between alkali-felspar and quartz and also constituting numerous spherulites. Some quartz phenocrysts have octahedral inclusions, each of which invariably enclose an immobile bubble. Section T.15 shows many needle-like pseudomorphs recalling the hornblende needles in pitchstone. A few grains of iron-ore, zircon and needles of apatite are seen. Some grains of zircon are attached to brownish pseudomorphs which probably represent original augite. Many of the quartz phenocrysts are the nucleii of sperulites a few of which show microlites, recalling similar features in pitchstones. All these features suggest that the quartz-felsite is a devitrified pitchstone.

Pitchstone: (Specific gravity: 2.411; Plate VI, Fig.4). The rock is/

is very well described in the Arran memoir as the Tormore type (1928, p.230). A few words may be added about the interesting pyroxenes seen in the rock. Many of them have quite a high relief, give straight extinction, and some are distinctly pleochroic like hypersthene. Optically they are positive, and the nature of the isogyres gives the impression that the mineral is uniaxial. Since the R.I. is higher than is usual for rhombic pyroxene and since the mineral is optically positive, the pyroxene is probably pigeonitic in character. The olivine which is an iron-rich fayalite, is optically negative. The crystallization of fayalite in silica-rich rocks is discussed by Scott (1914, pp. 18-20) and Tyrrell (1928, pp.231-2) quotes the works of Hawkes and Fenner. Fayalite probably crystallises at a late stage since it is the low-temperature form of the olivine mix-crystal series. Iron-ore occurs to a greater extent than is usual in pitchstones and is associated with zircon. The volume percentages obtained with Dr. A.T.J. Dollar's Integrating Micrometer reveal the richness in mafic minerals of this pitchstone.

TABLE I.

Olivine.	Free quartz.	Pyroxenes.	Microlites.	Felspar.	Iron-ore.	Glassy base.
0.6	2.6	3.6	13.2	11.9	1.0	67.2

The/

The occurrence of the pitchstone between the tholeiite and the quartz-felsite and on only one side of the dyke indicates that in all probability it is later than the main dyke, an idea shared by Judd who believed that the dyke complex must have been filled in three distinct stages (op.cit., p. 556).

The absence of a chilled margin between the tholeiite and the quartz-felsite, the presence of xenocrysts in the former rock similar to the phenocrysts of the latter suggesting a possible relationship between the two, demonstrate that Judd's No. II dyke is composite according to modern teminology.

THE MIDDLE TRANSVERSE DYKE.

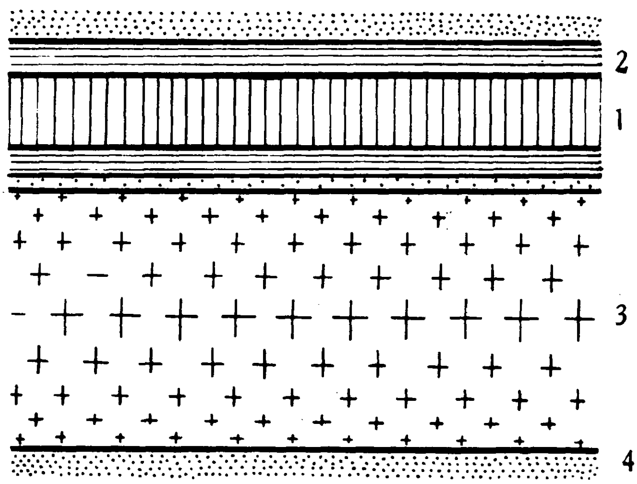
(Judd's No. III dyke on Tormore Shore).

The results of the author's study in the field showed a great divergence from that of Judd, clearly seen from a comparison of the two plans (1893, p.556 and Plate XI & Fig.3). The 'augite-andesite' of Judd occurs only on the southern side and is completely absent from the north. Detailed study showed that this intrusion is actually composed of two different dykes; the southern dyke is a highly altered coarse-grained olivine-dolerite and the northern dyke is centrally composed of pitchstone with banded quartz-felsite on either side. Between the two dykes can be recognised in some places quartzite representing the sedimentary rock of the area hardened by contact metamorphism.

PETROGRAPHY/

Fig. 3. The Middle transverse dyke.
(JUDD'S No. III)

NOT TO SCALE



1. Pitchstone.
2. Banded felsite.
3. Olivine - dolerite.
4. Sedimentary rock.

PETROGRAPHY.

Olivine-dolerite: (Specific gravity: 2.789). The rock is very coarse-grained in the centre of the dyke, becoming fine-grained on either side indicating chilling against the country rock. The thin section shows that it is not a tholeiite as described by Tyrrell (1928, p. 220) but an olivine-dolerite, composed mainly of lilac-brown pleochroic titanaugite, in subophitic or ophitic relationship with laths of labradorite (Plate VII, Fig.1). The olivine is present only as pseudomorphs of serpentine. Iron-ore occurs in large irregular plates. There are circular areas filled with fibrous zeolites as well as with pale brown isotropic analcite. There are no xenocrysts of any kind in contradistinction to those in other basic rocks which form parts of composite intrusions (cf.p.12). Olivine-dolerite is quite common as individual dykes both on the Tormore shore and at Drumadoon.

Pitchstone: (Specific gravity: 2.286). This yellowish green rock is very different from other pitchstones of Tormore; it is poor in ferromagnesian minerals, and microlites (arborescent etc.,) described commonly from pitchstones are absent. It is composed of corroded phenocrysts of quartz, a few indistinctly zoned crystals of mid oligoclase with multiple-twinning and with occasional glassy inclusions, and some grains of iron-ore associated with euhedral zircon. All these minerals are set

in/

in a glassy and partly devitrified base traversed by numerous cracks and showing flow-oriented crystallites.

Banded quartz-felsite: This rock occurs on either side of the pitchstone. It shows microphenocrysts of corroded quartz in the handspecimen. In thin section the quartz-felsite appears to be similar in composition to the central pitchstone and also shows flow-oriented crystallites which differ in their number and size in the different bands (Ar.203). The base of the rock is traversed by cracks and shows variation in the amount of devitrification. The contact between the non-banded pitchstone and the banded quartz-felsite is apparently sharp, but in view of the petrographic similarities of the rocks, the felsite appears to be a devitrified form of the pitchstome.

CIR MHOR DYKE.

(Judd's No. IV dyke).

Although this dyke was not studied in the field by the author, the rock-slides from Dr. G.W. Tyrrell's collection were studied for purposes of comparison with the other dykes. The field relations of the dyke are described both by Judd (op.cit., pp. 544-5) and Tyrrell (1928, p.208). It consists centrally of pitchstone (Plate VII, Fig.3) which is flanked on both sides by quartz-felsite (Plate VII, Fig.4). The marginal member occurring on either side is a tholeiite. Microscopic examination clearly reveals/

reveals that the quartz-felsite is a devitrified facies of the pitchstone since both the rocks show similarities in petrography. The felsite has a devitrified base and shows numerous pseudomorphs of crystallites probably of original hornblende, a feature similar to the quartz-felsite of Judd No. II dyke. Judd describes a continuous passage from the pitchstone into quartz-felsite. The phenocrysts of quartz and felspar are similar in both rocks.

The basic rock is also very similar to the tholeiite of Judd's No. II dyke. Section Ar.189 reveals a small xenocryst of quartz (Plate VII, Fig.2) with the typical rim of granular augite, though the Geological Survey slide (25169) does not show any similar grains. Judd records (op.cit., p. 547) the presence of "greatly corroded crystals surrounded by zones of secondary augite" and he is obviously referring to these xenocrysts of quartz. In addition to such undoubted quartz xenocrysts the slides reveal many xenocrysts of felspar showing evidence of corrosion similar to those in the tholeiite of Judd's No.II dyke. It is interesting to note that here also the size of the xenocrysts bear a close resemblance to that of the phenocrysts in the acid rock.

To/

To sum up, the revision of Judd's famous work brings out the following points:-

(a) The great north and south dyke (No.I) is not composite according to modern terminology, but is multiple.

(b) The middle transverse dyke (No.III) is actually composed of two distinct dykes and is not composite.

(c) Only the north transverse dyke (No.II) and the Cir Mhor dyke are truly composite.

The many divergences seen in the author's study of the dykes from Tormore shore from that of Judd must be attributed to the fact that "no two observers have seen the shore in quite the same condition. The tidal scour sweeping loose blocks and shingle into hollows at times obscures certain tracts of shore or at other times uncovers other portions of it." (Judd, op.cit., p.556).

THE DRUMADOON INTRUSIONS.

FIELD DESCRIPTION.

(a) Sill.

The striking columnar cliffs at Drumadoon Point form a conspicuous landmark on the west coast of Arran. The whole mass has been emplaced horizontally as a sill into the sediments which can be seen in the lower part of the cliffs. The sill is composite in nature with quartz-porphyry forming the main portion, and a subordinate sheet of basalt, xenoporphyritic with quartz and felspar, at the base. The porphyry is about 100 ft. thick; the basalt sheet which is well exposed at the foot of the cliffs, varies in thickness from 2-4 ft. in the north to 2-2½ ft. in the south, where it cannot be traced any further and gives place to the porphyry. In at least two places the basalt appears to take sharp plunges downwards and again pass horizontally.

What appears to be a contact between the basalt and the porphyry can be traced along a thin zone of alteration and at only one place is the actual contact preserved. The basalt does not show any chilling against the porphyry but chills against the sediment which is itself little affected. Above the line of contact are seen many large oval or rounded irregular xenoliths about 1-1½ ft. in diameter and they can be traced to about 25 ft. above the base of the sill (Plate II). They are similar in grain-size and in their xenocrysts to the underlying basalt, of which they presumably formed a part originally. Hence the basalt must/

must be earlier in sequence than the porphyry. The dark porphyry enclosing the xenoliths appears to have had very little effect on them (cf. descriptions of Smellie in Bute, 1912-15, pp.121-139). In the southern part of the sill at least two thin veins (2-4 ins.) of tachylyte were seen cutting through the basalt, the porphyry and xenoliths, and hence are later than the composite intrusion.

Examination of the top of the Doon did not reveal any relics of basalt, though Tyrrell remarks that "the very thin upper sheet of basalt can be identified by fragments on the summit of the Doon..." (1928, p.200). The quartz-porphyry here is strikingly light grey in contrast to the very dark porphyry at the base. Another conspicuous difference is the absence of xenoliths on the western side of the top of the Doon. (cf,Harker's descriptions from Skye, 1904, p.222).

For about 500 yards along the shore at Drumadoon Point stretching in a north-south direction can be seen a mass of quartz-porphyry similar to that in the cliffs (Plate XI). This mass with an associated and overlying sheet (2-4 ft. thick) of xenoporphyritic basalt plunges eastward, at angles varying from 20°-40°, very well seen in the sandy beach at Drumadoon Point (Plate I). Further south very near the sea, the sheet shows variations in directions within short distances, which is well seen/

seen at low-tide. An apparently sharp contact can be recognised between the basalt and the porphyry but they do not show any chilling against one another. The absence of xenoliths and the lighter colour of the porphyry bear close resemblance to similar features on top of the Doon.

The northern part of the porphyry mass of the shore is complex. The porphyry becomes dark grey, shows a number of xenoliths of basalt and is terminated by an E-W. basaltic dyke which is xenoporphyritic like the basalt sheets associated with the composite sill and shows a highly irregular and occasionally merging contact with the porphyry on the one side and chilling against the sediment on the other.

The precise relationship between the mass at Drumadoon Point and the sill at a higher level at the Doon is somewhat obscure and according to Tyrrell "the mass at Drumadoon Point is either injected on a lower horizon than that which appears in the columnar cliff or has been thrown down to the south along an east-west fault line." (1928, p.200).

The following points appear to favour the view that faulting has been responsible for the present relationship of the two masses:

(a) The disappearance of the lower basalt in the southern region of the sill at the Doon.

(b)/

(b) The resemblance of the porphyry in the upper part of the Doon with the porphyry below the overlying basalt sheet at Drumadoon Point, in the light colour and absence of xenoliths.

(c) The occurrence of a crushed rock at lower levels towards the southern end of the sill at the Doon. In thin section the minerals of the rock, especially the quartz and felspar phenocrysts are crushed. This crushed porphyry does not occur at higher levels.

(d) The complex nature of the northern part of the lower mass on the shore and the presence of the xenoporphyritic basalt dyke.

(e) An examination of Plate XI will show that the lower mass on the shore terminates along a line almost exactly where the upper mass at the Doon begins, and this strongly suggests a fault between them.

The faulting was probably complex; (i) it was presumably a reverse fault, (ii) there was westward displacement, and (iii) the present inclined nature of the lower mass compared to the horizontal nature of the upper mass suggests that the fault was rotational. The intrusion of the xenoporphyritic basalt (e) probably took place along the east-west fault plane.

In the new one inch geological map of Arran (1947) both the/

the masses are shown as one connected mass, whereas in the old map (1910) they are shown as two distinct masses. The author believes that the mapping shown in the old map is correct (Plate XI).

Both the masses are cut by basalt and dolerite dykes, mostly in E.-W. but also in N.-S. directions.

(b) Drumadoon dyke.

About 300 yards east of Drumadoon Point there is a thick dyke (25-27 ft.) composed of mainly quartz-porphyry extending into the sea for about two furlongs (30° E. of N.). On either side of this porphyry, basaltic xenoliths can be recognised which are evidently the only relics of the original basic rock. The southern part of the dyke has suffered displacement due east very near the low-water mark, but there are no other signs of faulting. Further north the dyke is seen in the sand dune in a highly weathered state. On the eastern side of the Doon, the dyke is in the form of a ridge (37° E. of N.) and there is apparently a change in the direction (50° E. of N.) which may be the result of faulting though there is no direct evidence. The dyke has a vertical contact with red and yellow sandstone and marls which are well exposed to the west.

It is difficult to recognise the dyke beyond the old quarry marked on the 6 inch sheet (Buteshire, 253 N.E.), since it/

Fig. 4. Composite dyke at Cleiteadh nan Sgarbh, half a mile north of Drumadoon.

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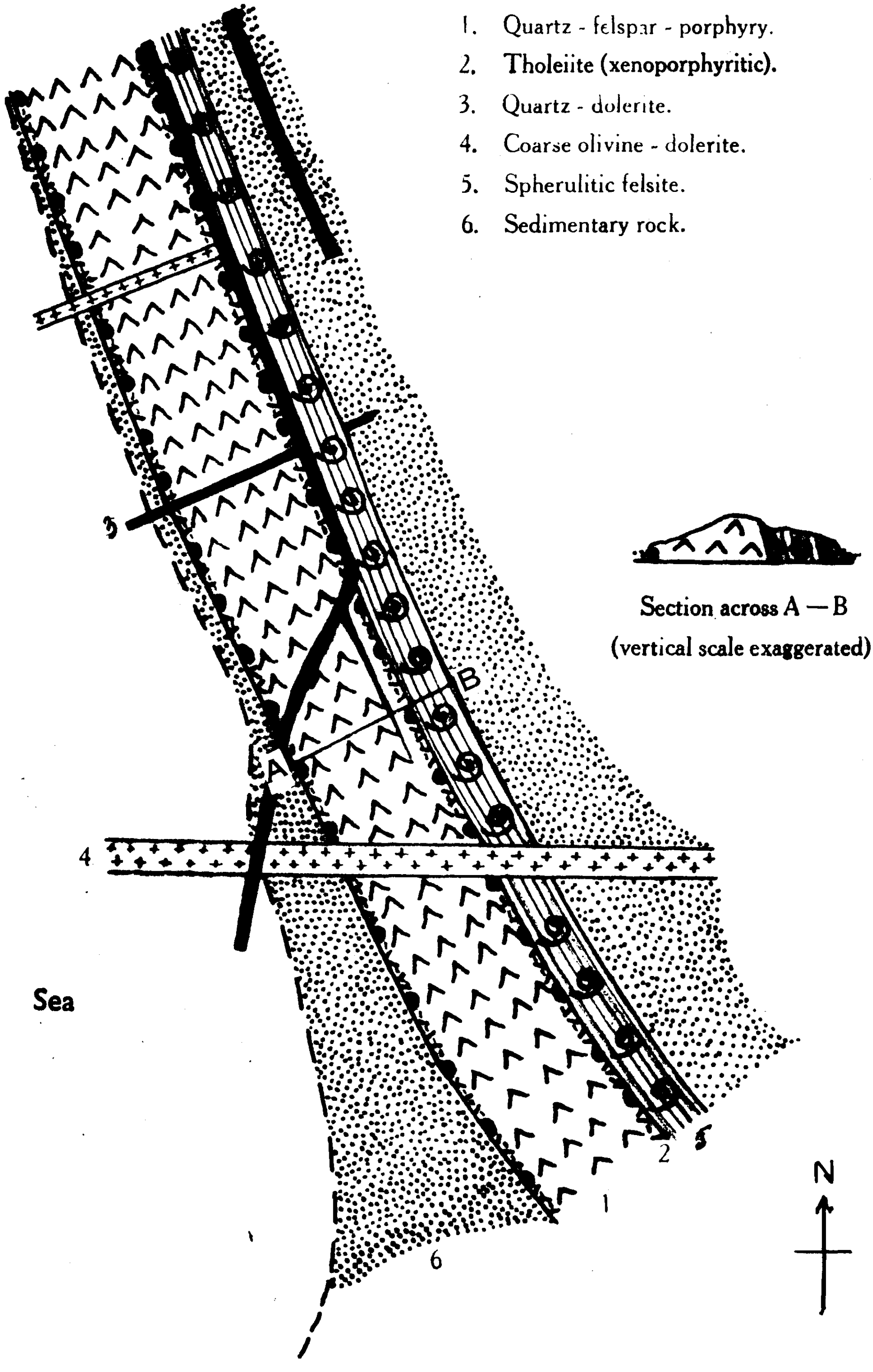
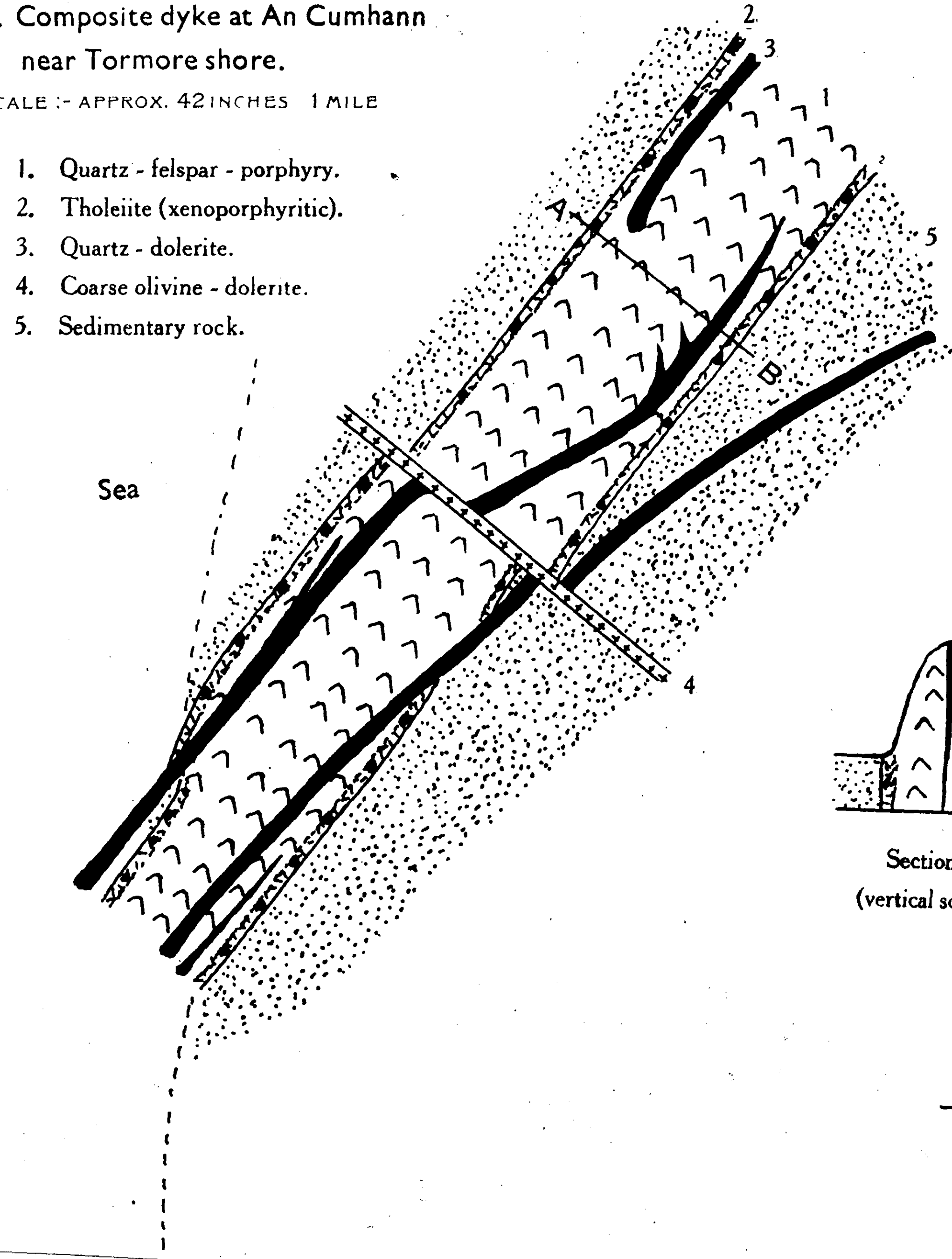


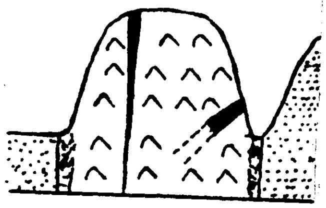
it is obscured by the old fort-wall of the Doon, but the presence of dark and xenolithic porphyry on the eastern side of the Doon may indicate a further extension. North of the Doon, the dyke passes from the cliffs on to the shore (40° W. of N.) hading at a high angle due N.E. and a few yards beyond the hade changes to a S.W. direction. A banded felsite makes its appearance first in the cliffs and thence along the entire eastern margin of the composite dyke. On the shore near Cleiteadh nan Sgarbh (Fig.4), remnants of the basaltic members (2-2½ ft. wide) can be recognised; the section here is as shown by Tyrrell (1928, p.200) except that the dyke complex is actually dipping due east at a high angle (Plate III). The outcrop of the dyke extends for about 400 yards until it is submerged by the sea. There are several parallel and oblique dykes of basalt and dolerite cutting the composite dyke and since all of them chill against it, are later in age.

Three-quarters of a mile further north at An Cumhann near the Tormore shore, the same dyke reappears (Judd's No.IV, 1893, p.557) striking 50° E. of N. forming a 'great buttress' across the shore (Plate XI). Here it is a vertical body and is flanked by sheets of basalt of about 3 ft. in width on either side, which show chilled contacts with the sediment and merging contacts with the porphyry. As at Cleiteadh nan Sgarbh, here also/

Fig. 5. Composite dyke at An Cumhann near Tormore shore.

SCALE :- APPROX. 42 INCHES 1 MILE





Section across A — B
(vertical scale exaggerated)

also there are dykes of later age which cut the main dyke obliquely, but there is no associated felsite. One N.W.-S.E. dyke causes a displacement of the northern part of the dyke complex in a north-westerly direction. The composite dyke can be traced inland only for some distance, but is then lost.

The thickness of the dyke complex varies from place to place depending on the number and thickness of the later dykes. It is least at Drumadoon (25 ft.) but is 51 ft. at Cleiteadh nan Sgarbh and 63 ft. at An Cumhann.

PETROLOGY.

Basic Rock: Tholeiite.

The basic member of both the sill and the dyke is a fine-grained, dark grey basaltic rock, xenoporphyritic with rounded or irregular xenocrysts of smoky quartz about 1-3 mm. in diameter and dark grey felspar recognisable only by the reflections from its cleavage plates. There is very little variation in the grain size of the rock except in the chilled margin where it is very fine-grained. On alteration, the rock becomes brownish in colour due to its high iron content. The specific gravity of the rock is 2.783 and that of the chilled margin is 2.66. The appreciable difference between the two values may be in part due to the invariably altered nature of the chilled margin, though the possibility of a difference in the/

the amount of mafic constituents cannot be excluded.

Microscopically the rock is composed of prisms of plagioclase, grains of augite and iron-ore, with subordinate rhombic pyroxene, in a matrix consisting of intersertal dark brown or cryptocrystalline material, which has microlites of felspar and skeletal iron-ore (Plate VIII, Fig.1). There are xenocrysts of quartz and felspar. Apart from its xenocrystic material, the rock is comparable to the tholeiite of Brunton type described from Mull (Memoir, 1924, p.372).

Plagioclase shows considerable variation in grain size. A few large anhedral crystals assume the proportions of phenocrysts; they are mostly multiple-twinned but are occasionally untwinned. A great majority of the grains occur as small, multiple-twinned prisms, short and stout, or elongated and blade-like. In many cases they are moulded on earlier formed augite. Sometimes a few prisms are subophitic towards augite. The R.I. is high and the prisms give an extinction angle of 31^{o}-37^{o} and hence are mainly acid labradorite. Numerous skeletal crystals of felspar are found in the interstitial material. When, as in some parts of the dyke the rock occurs as xenoliths, the plagioclase is partially replaced by carbonate.

Augite also occurs as large sporadic grains, euhedral or subhedral and sometimes with multiple-twinning, but is principally found as colourless or very pale pink granules. Some crystals show subophitic/

subophitic relation with plagioclase, while in some sections the augite shows a tendency to develop in glomeroporphyritic aggregates. The mineral shows high relief, high birefringence and a partial or complete alteration to carbonate and chlorite.
Rhombic pyroxene: In some sections (Ar.7376) a few grains can be clearly recognised by their straight extinction as rhombic pyroxene. They are feebly pleochroic from very pale brown to very pale green and alter to chlorite, which is pleochroic from yellowish green to dark green, having low polarization colours and positive elongation. In some of the sections studied there are chloritic pseudomorphs, many of which are euhedral and probably represent rhombic pyroxene.
Iron-ore is an important accessory occurring as small irregular grains and occasional rods but in the base has a skeletal habit.
Base: In many sections, there is dark brownish glassy or cryptocrystalline material occurring interstitially, with microlites of felspar and skeletal iron-ore and a few grains of quartz. In a few sections such as D.24 the microlites etc., take up a great deal of space in relation to the amount of glassy base. Some sections show flakes of biotite in the groundmass.

Xenocrysts.

Quartz occurs as rounded irregular grains with inclusions similar to those found in the porphyry. Ar.216 shows a xenocryst of quartz with inclusions of calcite and zircon, the latter being a typical mineral of the acid rock. The xenocrysts are mostly surrounded/

surrounded by narrow rims of granular augite which is generally altered to carbonate and chlorite (Plate VIII, fig.1). Rhombic pyroxene is absent from these rims.

Felspar xenocrysts are usually much larger than quartz xenocrysts. They show abundant evidence of corrosion, especially in the interiors which in consequence have a pitted appearance. In some the cores remain intact, but are surrounded by corroded exteriors. A few of these crystals are multiple-twinned with a low extinction angle (0^o-15^o) and hence are mid to basic oligoclase in composition, while others are untwinned orthoclase. Many of them are traversed by transverse cracks while along their cleavages occur skeletal crystals of iron-ore and irregular grains of augite. All these xenocrysts invariably show narrow rims of felspar of higher relief similar to the felspar of the rock, obviously a later addition.

Drusy Cavities.

The tholeiites of Drumadoon show numerous drusy cavities consisting of the glassy or cryptocrystalline base, carbonate, fibrous chlorite, quartz, microlites of plagioclase, and skeletal iron-ore. Some sections such as D.2 and D.18 a. show large patches composed of numerous fan shaped microlites of felspar with high relief (acid andesine) and are devoid of any mafic minerals. The microlites radiate from irregular plates of felspar giving the impression that they were formed by rapid crystallisation induced by interaction with xenocrysts of felspar (Plate VIII, Fig.1).

The/

The chilled margin of the tholeiite is generally very altered, showing large prisms of felspar partly replaced by carbonate; sometimes the prisms segregate into glomeroporphyritic groups. The augite is generally altered into chlorite. The groundmass is composed of a felt of small microlites of felspar and dusty or skeletal iron-ore. There are xenocrysts of quartz with altered augite rims and also corroded felspar xenocrysts with rims of fresh felspar.

The tholeiite of the sill and dyke show little variation except in the amount of the base. In some places, as in parts of the dyke where the rock is preserved only as xenoliths, the tholeiite appears to be coarser in grain.

Acid rock: Quartz-felspar-porphyry.

(Specific gravity: 2.546).

The acid component of these intrusions is a quartz-felspar-porphyry which occurs both uncontaminated and contaminated with basic material. The former, found on top of the Doon, in the southern part of the lower mass at Drumadoon Point and also in the dyke, is a light grey megaporphyritic rock with rounded or oval phenocrysts of smoky quartz and euhedral plates of felspar set in a light grey compact groundmass. The felspar grains usually show alteration; some have a white margin and a glassy-looking interior.

Microscopically/

Microscopically the rock is composed of phenocrysts of quartz and felspar which includes both orthoclase and plagioclase, altered mafic minerals and iron-ore, set in a cryptocrystalline groundmass which also contains irregular grains of quartz (Plate VIII, Fig.4). The rock is described as a quartz-porphyry in the Arran memoir (1928, p.204), but it is considered that the term 'quartz-felspar-porphyry' better describes the rock in which the felspar phenocrysts form such a conspicuous and characteristic part.

Quartz occurs mostly as phenocrysts with rounded or oval outline; sometimes the crystal form can be recognised despite corrosion of the edges. Although from their size in relation to the groundmass these grains have to be described as phenocrysts, the crystals vary in size, suggesting that many of them were not confined only to one period of crystallisation. They show inclusions of the groundmass, sometimes of carbonate, but in a few cases there occur squarish or octahedral inclusions, each of which invariably contains an immobile bubble.

Felspar which includes both orthoclase and plagioclase, usually occurs in rectangular grains larger than those of the quartz. Composite grains formed by the intimate grouping of two or three crystals lying in different optic orientation, are common. In general the felspar crystals are partly altered; occasionally they appear as 'ghost-like' bodies due to high alteration. The crystals/

crystals sometimes show partial replacement by quartz and micropegmatite and also have inclusions of zircon. The orthoclase is mostly untwinned. The plagioclase is multiple-twinned with extinction angle 0^{o}-17^{o}, and corresponds to basic oligoclase, but ranging occasionally to acid andesine.

The generally altered nature of both the felspars and the absence of fresh grains of orthoclase showing even a single emergent optic axis rendered in most cases the determination of the optic axial angle on the Federov stage difficult. However, in section D.30 two orthoclase crystals occurring in an aggregate of small grains gave 2 V = 77^{o} and 71.5^{o} about X, suggesting that soda if present is only in small amount.

Pyroxene: (?) The sections show many pseudomorphs which consist of greenish yellow or brownish chlorite, carbonate, and secondary iron-ore; they are invariably associated with primary iron-ore, zircon and apatite. Nowhere is any original mineral preserved. From their shape, products of alteration and also by analogy with similar features noticed in the pitchstones in Tormore and elsewhere (Tyrrell, 1928, p.224), it is inferred that the aggregates are pseudomorphs after pyroxene.

Iron-ore in large irregular patches, occurs separately as well as in association with crystals of zircon.

The groundmass is generally composed of crypto-crystalline material, which appears to be mainly turbid alkali-felspar or micropegmatite which is a very fine intergrowth of quartz/

quartz and predominant alkali-felspar; but sometimes the groundmass is microgranitic due to the granular nature of the quartz and the turbid felspar. Usually numerous irregular grains of quartz are found in the groundmass. There is very little apatite. Drusy cavities with carbonate and irregular quartz grains are quite common.

The porphyry in parts of the dyke at Cleiteadh nan Sgarbh (D.48) has a pink groundmass due to iron-staining. The same rock shows replacement of felspar by a greenish, almost isotropic non-pleochroic mineral which is probably serpentine. The quartz-felspar-porphyry in the middle of the composite dyke at Drumadoon Bay shows an interesting variation in the groundmass which contains a large number of squarish or oblong untwinned alkali-felspar, replaced to some extent by chlorite; some of them form the nucleii of spherulites and semi-spherulites. Several irregular grains of quartz are also associated.

The greatest variation is seen in the dark grey porphyry both in the northern part of the lower mass on the shore at Drumadoon Point (D.16 and D.18) and in the lower part of the sill in the Doon (Ar.207, D.26 and D.27). Megascopically the difference lies in the very dark compact groundmass but even a cursory examination of the slides reveals the unusual richness of the rock in mafic constituents.

The/

The groundmass of the rock contains numerous augite grains partly or completely altered to chlorite and carbonate, some of which are associated with secondary iron-ore. Among the numerous felspar grains, many are small rectangular prisms of mid oligoclase showing multiple-twinning and with almost straight extinction, while others are blade-like basic andesine with higher relief and greater extinction angle (27^o).

In some sections (D.29) the felsparsare replaced by the groundmass and also by carbonate. A few sections such as D.26 show several xenoliths of both medium- and fine-grain. The fine-grained xenoliths, composed of a few altered prisms of felspar in a felt of felspar microlites, give the impression that they were derived from a chilled facies of the tholeiite. They differ in their grain-size from both the lower tholeiite and the predominant xenoliths. In addition to the large irregular grains of iron-ore and the associated zircon, there are innumerable small dusty grains of the ore. The proportion of the mafic constituents varies even in the same slide.

From the above description, it is clear that the porphyry has been basified by the incorporation of basic material. There is apparently no development of any new minerals such as biotite or of any new felspar, or even of an abundance of apatite, features generally exhibited by hybrid rocks. In some sections of the basified porphyry quartz grains with altered augite rims can be recognised/

recognised (D.30). These probably represent original xenocrysts of the basic rock incorporated by the porphyry. The basification of the porphyry is apparently more mechanical than chemical. The following table of volume percentages of various constituents of the basified porphyry shows the considerable amount of mafic constituents it has incorporated:

TABLE II.

Quartz(free & phenocrysts).	Mesostasis.	Mafic minerals.	Iron-ore.	Ortho-clase.	Plagio-clase.	Carbonate.
15.0	48.2	16.7	3.0	10.5	1.2	5.4

Harker has described a quartz-porphyry "rich in dark red biotite and oligoclase and distinctly more basic than the usual type," (Tyrrell, 1928, p.203) but the author was not able to trace any outcrops of such a rock.

Tholeiite --Quartz-felspar-porphyry Contact.

Sill: As already described, the contact between the lower sheet of the tholeiite and the porphyry is apparently sharp in the mass at the Doon. Microscopic examination of the contact shows very little interaction, but section D.X.(tholeiite) indicates/

indicates slight acidification in the form of interstitial quartz and the occurrence of a quartz phenocryst without a rim of augite. In the lower mass on the shore at Drumadoon Point the contact between the upper tholeiite and the porphyry is very well seen and here megascopically the interaction between the members is negligible. In thin section, however, (D.46) the contact is rather zig-zag, with a certain amount of local mechanical mixing (Plate VIII, Fig.2). On the porphyry side of the contact, there are patches of tholeiite, quartz with augite rims in addition to the normal phenocrysts, and corroded felspar xenocrysts with rims of fresh felspar. The only change undergone by the tholeiite appears to be the carbonatization of its pyroxene. The porphyry has evidently not been able to assimilate the augite rim surrounding the quartz xenocrysts; neither has basification resulted in the development of augite rims around the phenocrysts. The composition of the felspar appears to remain unchanged and there is no development of biotite or apatite. Apparently the interaction is more mechanical than chemical in the sill.

Dyke: In Drumadoon Bay the tholeiite is seen only as small xenoliths or is represented by disseminated laths of labradorite and pseudomorphs of pyroxene in the porphyry. The tholeiite is better preserved both at Cleiteadh nan Sgarbh and An Cumhann. Interaction between tholeiite and porphyry can been seen in both/

both places producing contact hybrids in which xenolithic relics of the former can be recognised (Plate IX, Fig.1). Acidification results in the breaking up of the basic rock by interstitial quartz and micropegmatite. Iron-ore associated with zircon also makes its appearance. In section D.63 quartz xenocrysts with both complete and incomplete rims occur, but the xenocrysts of felspar apparently undergo no compositional change. Hence it appears that in the composite dyke also hybridization processes are more mechanical than chemical, but they are more pronounced in the dyke than in the sill.

DYKES OF LATER AGE.

Felsite.

(Specific gravity: 2.416)

The felsite, occurring on the eastern margin of the composite dyke at Cleiteadh nan Sgarbh is about 33 ft. in thickness Its banded nature seen only in proximity to the composite dyke, gives the impression of plastic flow under pressure during its emplacement. The felsite is generally yellow but in some places is greyish white. Variations are seen in the number and size of contained spherulites.

In thin section the banded felsite shows a few phenocrysts which are probably pseudomorphs of felspar, and are apparently composed of a very fine intergrowth of micropegmatite. These/

These are set in a groundmass composed of spherulites and semi-spherulites, some of which have nucleii of felspar prisms besides a relatively coarse micropegmatite with apparently predominant quartz. The reddish colour of the banding is due to iron-staining.

The non-banded felsite appears to be more spherulitic than the banded rock and contains less numerous phenocrysts. The alkali-felspar appears to be in excess of the quartz in the groundmass micropegmatite. A few prisms presumably originally of felspar now occur as pseudomorphs composed of a very fine intergrowth of micropegmatite. The dark grey spherulites are surrounded by irregular grains of quartz.

Quartz-dolerite.

Many of the dykes cutting the composite dyke are dark grey, very fine-grained and non-porphyritic.

In thin section these rocks are composed of prisms of plagioclase, pyroxene, iron-ore, with a mesostasis of quartz and alkali-felspar. The rock may be described as a fine-grained quartz-dolerite and not as a tholeiite, since it does not contain the dark glassy groundmass typical of the latter.

Section D.51 shows a few anhedral grains of pale green augite and also crystals of plagioclase, both of which from their size/

size could be described as phenocrysts. The rock is largely composed of numerous prisms of basic andesine with extinction angle of 30°, but a few appear to be more basic as judged by their higher relief and greater extinction angle (39°) and hence are basic labradorite. The pyroxene of the rock is generally altered to chlorite. Iron-ore is present as irregular grains. Quartz occurs conspicuously as anhedral grains associated with alkali-felspar. There are drusy cavities with irregular grains of quartz, carbonate and alkali-felspar. The section shows a few circular or oval patches composed of a very fine-grained basalt containing numerous altered pyroxene granules, iron-ore and a few grains of quartz. These patches appear to be cognate xenoliths.

Tachylyte Veins.

As already noted, a few veins of tachylyte were seen cutting across the tholeiite and the porphyry in the sill at the Doon. Megascopically they are black and glassy (D.22 and D.23). In thin section they show a large number of crystals of many sizes, set in a dark glassy groundmass (Plate VIII, Fig.3). The phenocrysts of acid labradorite are euhedral and occasionally show faint zoning. Sometimes they enclose very dark rounded or oval globules arranged either regularly or haphazardly, which are probably of glass. In the groundmass the felspar occurs as numerous/

numerous small multiple-twinned prisms (basic andesine to acid labradorite), as well as many microlites. Pseudomorphs varying in size from large phenocrysts to small granules composed of chlorite, carbonate and occasionally secondary quartz are common. The shapes of some of the pseudomorphs are suggestive of pyroxene.

MECHANICS OF INTRUSION.

Relationship between the composite dyke and sill.

There are no field exposures which give any conclusive evidence regarding the mutual relations between the sill and the dyke, but the close spatial association of the two bodies, and the appearance of dark xenolithic quartz-felspar-porphyry on the eastern side of the Doon (p.22) are significant. Petrographically the tholeiite of the sill is similar to the tholeiite of the dyke and the porphyry especially the uncontaminated rock, compares closely with the acid rock of the dyke. Hence it is reasonable to conclude that the dyke and the sill are genetically related and that in all probability the dyke was the feeder of the sill. Harker's observation that "in every case where composite sills are found, there is a dyke ... at no great distance," (1904, p.211) lends support to this view.

The main difference between the sill and the dyke is in the degree of interaction between their basic and acid members. (p.34). The greater extent of contact hybridization observed in the/

the composite dyke than in the composite sill suggests that the magma had more thermal energy when it was emplaced in the dyke than in the sill. This is readily explicable if the dyke fissure be regarded as the channel for the introduction of magma to form the sill.

As already described, the contaminated porphyry at the base of the sill is the result of incorporation of basic material which includes xenoliths of medium- and fine-grain (p.31). It is likely that some of the xenoliths especially the fine-grained material were picked up during the emplacement of the acid magma and represent the basic rock adhering to the country rock (cf. Smellie, 1912-15). The process can be imagined to have taken place as follows. The tholeiite was first injected along the bedding planes of the sediments. Later the porphyry was emplaced and "entered along the lines of least resistance, namely the planes of weakness, dividing the margin from the interior" of the basic rock, as imagined by Smellie in Bute (op.cit., p.125). If a large volume of acid magma in excess of the volume of the basic was emplaced, part of it will eviscerate the basic rock as it works its way through it becoming hybrid in this process, and the rest will remain uhcontaminated. This is strongly suggested by the absence of xenoliths and the uncontaminated nature of the porphyry at the top of the sill.

The sill was affected by an E.-W. fault along which

there/

there appears to have been a recurrence of intrustion of the basic magma as a dyke. Zones of tension developed over the whole area and were injected by dykes of a later age. The field relationships of the dykes at Cleiteadh nan Sharbh (Fig.4.) show that the fine-grained quartz-dolerite cuts an olivine-dolerite dyke and hence is later. The banded felsite cuts both of them and therefore was the last to be injected in this area.

BENNAN INTRUSIONS.

In the south of Arran a largely drift-covered mass of quartz-porphyry with a width of 1½ miles is shown in the one inch geological map of the island (1947), extending in a south-south-easterly direction from Cnoc Clauchag, three miles N.N.E. of Lagg. The mass is well exposed near and along the Struey burn where it is flanked by sheets of dolerite seen prominently in the Cairn to the north, and at Bennan Head to the south. The margin of the intrusion can be traced for some distance further east whence its trend is seen to change to a northerly direction, extending for three quarters of a mile along Creag Dhubh, where good exposures are found in two quarries. It is shown in the map to terminate in a hook shaped fashion.

Besides the main mass, the following minor bodies occur in the same area: (1) a small N.W.-S.E. dyke-like mass of basic rock (M) about 200 yards north-east of Smithy; (2) a second dyke-like mass (QD) about 250 yards north of Creag Dhubh quarry and (3) a mile-long mass of quartz-porphyry and quartz-dolerite (QD) forming the ridge of Torr a' Bheannain about 300 yards north of (2); the dolerite occurs as a thin layer in the west flanking the porphyry, becoming wide in the east and extending southwards as the Levencorroch hills (Plate XII).

FORM OF THE INTRUSIONS.

(1) The Bennan Mass.

This mass has been injected into horizontal or gently inclined Keuper marls and sandstones which are well exposed at a few places. The form of the intrusion can be best studied by tracing the nature of its contacts with the country rock.

(a) Upper contact.

Starting from the north-west of the intrusion, the first exposure studied is seen in an old quarry section of xenoporphyritic basalt north-east of the Smithy, but the contact with the sediment cannot be recognised. The grain-size of the rock is very fine at the top but becomes coarser about five feet below. Where the basalt is exposed at the surface, it appears to have a dip of about 10^{o} changing to 20^{o} in a 60^{o} E. of N. direction, leading to the inference that the mass as a whole has a low dip in this neighbourhood. About 200 yards south-west of the west Bennan farm, basalt occurs in a prominent mound with a small quarry wherein the rock is very well exposed. This mass is very similar to the basalt near the Smithy in dip, grain-size as well as its xenoporphyritic nature. In view of the close similarity of both these masses with the predominant upper basic member of the Bennan mass, they presumably form parts of the main body. The author considers that the basalt near the Smithy is not a separate dyke-like mass as shown in the one inch map.

The intrusion is obscured further south-east by

agricultural/

agricultural land till the hills near the Cairn are approached. Although the actual junction with the sediment cannot be recognised here, from a study of the dolerite-porphyry contact zone, it can be inferred that the upper sheet has a dip of about 40° to the N. To the east of the Cairn, there are a few isolated exposures; the mass becomes dyke-like along Creag Dhubh. The contact is presumably highly inclined near the east Bennan farm. Further north the position of the contact becomes obscure.

(b) Lower Contact.

About 500 yards west of Struey waterfalls along the shore at Bennan Head, the lower contact which is presumably dipping steeply to the north, can be traced downwards to the shore. Near the Black cave east of the waterfalls, at least four large rafts of more or less horizontal sediments are enclosed by the intrusion. Careful examination of the shore reveals tongues of basalt injected into the horizontal sediments. Hence it is probable that the lower contact is dipping at a low angle, contrary to the idea held by Gunn that the contact plunges steeply into the sediments (quoted by Tyrrell, 1928, p. 197). Tyrrell's section along the Struey water at Bennan Head also shows rather a low dip (op.cit., p. 198).

To the east of Black cave the intrusion can be traced

on/

on the shore but the contact itself is obscured. About half a mile east of the Black cave and clearly exposed in the cliffs, the intrusion makes a steep contact with the sediment. On the eastern side of Creag Dhubh the contact cannot be recognised. From the exposures in the small quarry north of Creag Dhubh quarry, its position is inferred to dip at a high angle with the sediments.

Hence, the Bennan mass is a complex sheeted body; the section along the Struey burn suggests a predominantly laccolithic habit, but the eastern extremity of the mass is evidently dyke-like. The upper and lower sheets of basic rock are presumed to envelop the terminal part of the porphyry, but this conclusion is purely conjectural since it receives no confirmation from actual outcrops.

(2) Intrusions of the North.

Detailed examination of the Torr a' Bheannain mass shows that it is very similar to the dyke-like mass at Creag Dhubh in the south and is composed of quartz-porphyry and dolerite. The latter rock which occurs in the cliffs along the western margin can be traced northwards where it changes in direction and envelopes the porphyry. To the east of the Torr, along the western side of the steep U-shaped glaciated valley, the rock if present is obscured by peat, but the occurrence of numerous xenoliths of basic rock in the south-eastern end of the valley/

valley provides the only direct evidence. The opposing hill to the east is formed of an entirely different rock, a coarse-grained quartz-dolerite which is a continuation of the Levencorroch sill, and hence is not part of the composite mass as shown in the one inch map of Arran (1910 and 1947).

Though it is very tempting to relate the southern mass at Creag Dhubh to the northern mass at Torr a' Bheannain in view of their similarity in rock-types, direction and dyke-like forms, it was not possible to trace any direct connection between the masses. As already described, between the two there is a small outcrop of basalt (QD) clearly exposed along a small stream, which is actually a horizontal sheet and is similar to the dolerite of the main intrusions.

COMPONENTS OF THE BENNAN INTRUSION.

The Bennan intrusion has been hitherto described as a triple composite sill, but the following study shows clearly that it is actually of even more complex character.

The exposures along the Struey burn provide the most complete section through the sill (Fig.6). At the Cairn the upper dolerite (about 20 yards wide) passes rapidly to the south into quartz-porphyry with xenoliths of dolerite. About 10 yards south of this there occur exposures of a medium-grained rock, very different from both the porphyry and the dolerite. It/

It is a peculiar hybrid rock judging from its colour, non-porphyritic nature and the blade-like nature of pyroxene and felspar. The next 15 to 20 yards consist of basified porphyry; the hybrid rock reappears for a few feet giving place to dark basified porphyry and finally to a creamy white porphyry which extends for about 50 yards.

Extending for nearly 50 yards beyond this point, there occurs a very interesting zone composed of numerous large rounded or oval basic xenoliths enveloped in porphyry. This xenolithic zone which has not been described hitherto, can be traced laterally to the east of the burn in a few isolated exposures for about 140 yards, but it was impossible to find any exposures farther west, which is all agricultural land.

South of this xenolithic zone, porphyry free from xenoliths occurs for about 140 yards until the first small waterfall is reached (Fig.6) where again the rock becomes highly xenolithic. This zone extends a little beyond the second larger waterfall in the Struey gorge and passes rapidly into a coarse dolerite. Very near the third waterfall, the peculiar hybrid rock similar to that near the Cairn, is again seen. This is succeeded by fine-grained xenoporphyritic rock which is basalt-like in appearance.

About/

About eight feet from the ground to the east of the Black cave, an interesting contact can be traced for a short distance between two sheets of similar xenoporphyritic basalts of which the upper is chilled against the lower, while the latter is unchilled. This occurrence of two sheets of the basalts suggests the possibility that the basic member as a whole may not be a simple body.

As already stated, the upper dolerite can be traced from the old quarry beyond the Smithy where it is probably gently inclined to the small quarry north of Creag Dhubh quarry, where it is vertical. The lower dolerite is exposed at various places in both these quarries and can be traced along the shore until it passes again into the cliffs west of Struey burn. The dolerites show the maximum width along the Struey burn section. The contact betwwen the dolerites and the inner porphyry is nowhere sharp, there being a continuous and rapid passage from the basic to the acid rock. Associated with this transition, xenoliths of basic rock are seen in the acid rock.

PETROLOGY.

Basic rock: Quartz-dolerite and its variants.

The basic member of the Bennan intrusion is almost always a medium-grained dolerite (specific gravity: 2.762); the chilled outer margin is very fine-grained (specific gravity: 2.667) and there is a coarse-grained rock in the Struey gorge.

The/

The average dolerite in handspecimen is dark grey and is composed of shining laths of felspar and dark mafic minerals. It is xenoporphyritic with irregular grains of smoky quartz and dark grey felspar which often reveal the effects of corrosion. The xenocrysts occur both in the chilled margin and throughout the body of the rock.

The texture varies but is most often subophitic. The rock is composed of augite and plagioclase as essential minerals, with iron-ore and quartz as important accessories; micropegmatite is always also associated. Hypersthene occurs only in a few rocks and is always in subordinate quantities. Harrison describes this rock as 'granodolerite,' a term used by Shand. In the Arran Memoir, Tyrrell describes the rock as a hypersthene-dolerite (1928, p.203). The rock in general appears to resemble the quartz-dolerite of Talaidh type described from Mull (Memoir, 1924, p.372) but with certain differences. Since hypersthene does not appear to be ubiquitous, a point noticed by Harrison also, it is considered that the rock should be described as quartz-dolerite, with or without hypersthene.

Augite: (23.8 per cent; volume percentages quoted below for various minerals were measured on slide No.24457, the analysed specimen). The mineral is mostly colourless or very pale yellow, sometimes pale brown; it is subhedral, ophitic or subophitic towards plagioclase/

plagioclase laths; the grains are often multiple-twinned but do not show any diallage striation. The mineral is invariably associated with iron-ore. It often occurs in two generations, the first as sporadic large phenocrysts, the second as small prisms which form the majority of the grains. The prisms have a tendency to group themselves into glomeroporphyritic aggregates. The mineral shows high relief and birefringence, is biaxial and optically positive. Optic axial angle measured on the Federov stage is 48° to 51° about Z, showing that the pyroxene is diopsidic in composition.

Augite appears to be more resistant to alteration than hypersthene but changes to chlorite and carbonate and sometimes to secondary iron-ore.

Hypersthene: (5.5 per cent). Where present, it is generally prismatic and sometimes euhedral; it is commonly irregular in outline due to alteration along the margins and cracks to green serpentine. The mineral is slightly coloured and is pleochroic as follows:- pale reddish brown = Z, very pale reddish brown = Y, and very pale green = X; Z>Y>X. It generally shows straight extinction, the relief is higher than that of augite while birefringence is low. Optic axial angle measured on the Federov stage is 67° to 71° around X, corresponding to 32-34 per cent. $FeSiO_3$ and 66-68 per cent. $MgSiO_3$ (Winchell, 1946, Part II, p.218).

The/

The hypersthene, which occurs only in the dolerite, appears to have been formed by direct crystallization from the basic magma, since it is nowhere in this area found in the rocks produced by contact hybridization.

Felspar: (36 per cent). The mineral occurs both as occasional large crystals and as long rectangular prisms or laths, mostly multiple-twinned according to albite and sometimes pericline laws. Though the felspar is generally fresh, some alteration is noticed in the outer zones of the felspar in the neighbourhood of the mesostasis. The prisms often penetrate augite in ophitic and subophitic relation. From its extinction angle of 27^{o} to 30^{o} and relief the felspar is basic andesine in composition. Most crystals show undulose extinction which is evidently not due to external pressure on the rocks, since only the felspars and not the mafic minerals exhibit this feature. In view of this undulose extinction and small grain-size, the optic axial angle could not be determined on the Federov stage. In the chilled margin, the felspars occur as skeletal crystals (swallow-tail etc).

Quartz varies in amount; 2.3 per cent. in No. 24457 and 6.2 per cent. in B.31. It occurs in almost all the rocks as irregular grains, many of which show undulose extinction. It is associated with cryptographic intergrowths largely composed of turbid alkali-felspar. Sometimes a few flakes of biotite and fibrous chlorite are found in the groundmass.

Apatite

Apatite varies in amount and in the size of the needles, but is usually small in quantity, occurring only in the quartz, felspar and micropegmatite, but never in the augite, indicating its later crystallization.

Iron-ore is an important accessory. It varies in amount (4.7 per cent. in No. 24457 and 7.1 per cent. in B.32), occurring mostly as irregular rods. In many sections mainly from near the Struey waterfalls (No.III), iron-ore completely or partially encloses prisms of plagioclase, giving the impression of ophitic or subophitic texture. Krostrõm describes similar structures from a dolerite and believes them to be due to the crystallization of iron-oxide at a rather late stage (1937, p.134).

Xenocrysts.

Quartz xenocrysts are always surrounded by broad rims of prismatic or granular augite (Plate IX, Fig.2). Quite often the xenocrysts are completely resorbed giving rise to nodules of augite in their place. Hypersthene never forms part of the rim. Similar rims and nodules of augite are also found in the chilled margin, suggesting that interaction between the quartz and the magma had already taken place before the intrusion.

In the basalt which occurs as a sheet between Creag Dhubh and Torr a' Bheannain, quartz is completely absent, its place being taken by spherulites of pleochroic fibrous chlorite and/

and carbonate, which are encircled by the usual augite rims. Felspar xenocrysts show abundant signs of corrosion. They are either multiple-twinned mid oligoclase or untwinned orthoclase. Most of them show cracks due to expansion as described by Harker (1904, p.220); along the cleavage cracks are seen skeletal iron-ore and augite (Plate IX, Fig.3). Many show a thin rim of felspar similar to that of the felspar of the rock, and clearly a later addition.

Some sections of dolerite such as B.44 show veins of acid material consisting of irregular grains of quartz, rectangular grains of untwinned alkali-felspar, needles of apatite and skeletal iron-ore, set in a micropegmatitic groundmass. The composition suggests that the veins have been formed from acidic material during the final stages of consolidation of the intrusion. A number of acid segregation veins about an inch wide were noticed cutting the lower dolerite. Similar veins are recorded by Harrison also (1925, p.178).

Variant of the basic rock.

The dolerite is almost of uniform medium-grain everywhere except in the Struey gorge where it becomes coarse and gabbroid (specific gravity: 2.767). It is interesting to note that this coarse dolerite (Plate IX, Fig.4) shows neither quartz nor felspar xenocrysts/

xenocrysts nor any evidence regarding their former presence such as augite nodules, etc. The rock does not contain any hypersthene. The felspar which is acid labradorite is more basic than that in the quartz-dolerite of this area. The rock contains both quartz and micropegmatite in the mesostasis. In the following table, volume percentages of the minerals of this coarse dolerite are compared with those of the average dolerite which shows that the former is less mafic and has more acid mesostasis than the latter.

TABLE III.

Rock.	Apatite.	Pyroxene.	Iron-ore.	Meso-stasis.	Felspar.
Coarse dolerite B.126	0.4	20.3	4.5	35.1	39.7
Hypersthene-dolerite	-	29.3	4.7	30.4	35.7

Acid Rock.

Quartz-felspar-porphyry.

The acid rock is light grey, megaporphyritic, with phenocrysts of felspar and rounded quartz. The rock resembles the uncontaminated porphyry on top of the Doon. (cf. p. 27). Its specific gravity is 2.53. Microscopically also it resembles the Doon rock, the important difference being in the nature of the/

the groundmass.

<u>Quartz</u>: (6.2 per cent; the values given in the following refer to the volume percentages measured on No. 24460, the analysed specimen). The mineral is usually corroded in outline; very few grains are euhedral. Inclusions of quartz, granophyre, laths of felspar, chlorite and also sometimes zircon are common. Many of the grains show optical continuity with the micropegmatite of the groundmass.

<u>Felspar</u> is comparatively abundant (18 per cent.) and includes both orthoclase (14.3 per cent) and plagioclase (3.7 per cent). It generally occurs as composite grains and shows variation in size. The orthoclase is similar to that in the Drumadoon porphyry and is often kaolinised. The plagioclase is mid oligoclase often showing twins like the peculiar chess-board twinning characteristic of albite (B.167 and B.123).

An interesting relationship is observed in the Bennan porphyry between the felspar phenocrysts (both orthoclase and plagioclase) and the micropegmatite of the groundmass. This feature is best displayed in the porphyry associated with the middle xenolithic zone. The outermost part of many of the phenocrysts are pseudomorphed by micropegmatite, the original outline being still recognisable. Sometimes the crystals are deeply embayed by the micropegmatite which is often in optical continuity/

continuity with the groundmass; the multiple-twinning of the plagioclase becomes obliterated, but remnants of the felspar show optical continuity establishing that they are relics of the same original crystal. Hence the author is led to believe that the felspar phenocrysts have been pseudomorphed to varying extents by the micropegmatite of the groundmass (Plate X, Figs. 2 & 3). Associated with the micropegmatite of the pseudomorphs can be seen many irregular grains of quartz, altered augite, zircon and iron-ore.

Pyroxene (?): As at Drumadoon the porphyry at Bennan also contains invariably pseudomorphs of (1) carbonate and chlorite, (2) iron-rich serpentine or uralite with secondary iron-ore, and (3) secondary quartz and flakes of biotite. Section B.119 shows pleochroic hornblende as part of a pseudomorph. The association of primary iron-ore, zircon and apatite with these pseudomorphs is very characteristic. The pseudomorphs presumably represent original pyroxene.

Iron-ore occurs as occasional large irregular grains invariably associated with euhedral zircon. Zircon may also occur independently. Sections B.108, B.138, and B.X. show oval grains of strongly pleochroic, deep red allanite.

As was already stated, the groundmass of the rocks show variations; (1) having a granophyric texture and composed of irregular/

irregular intergrowths between alkali-felspar and irregular blebs of quartz; abundant variations in intergrowth occur even in the same slide, some parts being micrographic, (2) having cryptographic texture and composed mostly of turbid alkali-felspar and partly semi-spherulites, associated with irregular quartz grains. This texture is much the less common of the two.

Felspar of the groundmass: Rectangular prisms of alkali-felspar with straight extinction and often showing multiple twinning occur sometimes as in a few rocks along the Struey burn.

Drusy cavities are generally rare but are common in the porphyry enclosing the xenoliths in the middle zone. They are composed of carbonate, quartz or chlorite.

The porphyry at different places does not vary very much petrographically. Even the megascopically dark-coloured rock is found to be the same porphyry under the microscope.

Contact Hybridization.

As already described in the field study, there is abundant mixing of the porphyry with the dolerite in the Bennan intrusions, the contact being a continuous zone of transition, generally about a foot or so broad. The following observations sum up the result of a study of many thin sections from various places in the area. As acidification of the basic rock progresses, the following changes are noticed:

Textural changes: The subophitic or ophitic texture of the dolerite is lost and the rock becomes granular.

Mineralogical/

Mineralogical changes:

(1) Augite. (a) A gradual decrease in amount,

(b) an increased tendency for alteration, and

(c) appearance of granules in place of prisms.

(2) Hypersthene: No distinct variation was recognisable.

(3) Felspar of the groundmass: very near the acid rock the basic andesine disappears, its place being taken by rectangular prisms of oligoclase.

(4) Iron-ore shows a remarkable change from the rod-like or irregular outlines to rounded granules which at the same time become larger in size and fewer in number.

(5) Pyroxene pseudomorphs: The occurrence of these pseudomorphs which are typical of the porphyry is a sure indication of acidification.

(6) The groundmass micropegmatite shows a gradual increase in amount (Table IV).

(7) Interstitial quartz becomes more abundant.

(8) Apatite needles which are hair-like in both the porphyry and the dolerite become larger in the hybrids.

(9) Biotite flakes are common in the hybrids.

(10) Xenocrysts: The changes undergone by the xenocrysts and their augite rims are interesting. As a result of resorption as acidification progresses the broad rims of augite become thinner and are/

are often narrow and incomplete. Moreover, the rims in some sections show non-fibrous pyrogenetic pleochroic hornblende and biotite along with the augite. This illustrates Bowen's remarks that "a granitic magma effectively supersaturated with biotite will react and convert the members of basic xenoliths to biotite by steps," (1922) and here the various steps of the discontinuous series are preserved evidently due to a failure of reaction going to completion. Very near the acid rock quartz phenocrysts occur besides the xenocrysts with narrow rims (Plate X, Fig.2). The changes are much less explicit in the felspar xenocrysts but some show development of peripheral outgrowths of felspar prisms (B.72).

The following table of volume percentages of two rocks taken at close intervals illustrates clearly many of the points described above.

TABLE IV.

Rock.	Augite.	Plagioclase.	Mesostasis.	Iron-ore.	Free Quartz.
B.31. Quartz-dolerite	26.8	40.0	11.0	7.1	6.2
B.32. Acidified dolerite	19.0	24.2	43.8	4.9	7.3

Specific/

Specific gravities of the rock specimens give a very good indication of acidification and have been used by several authors. The table below shows how there is a decrease in specific gravity as acidification progresses.

TABLE V.

Specimen.		Distance in feet.	Specific gravity.
B.66	Dolerite	2' from outer contact	2.751
B.68		8' " " "	2.767
B.69		15' " " "	2.746
B.70		20' " " "	2.702
B.71		30' " " "	2.686
B.72		36' " " "	2.670
B.73		38' " " "	2.643
B.76		41' " " "	2.534
B.81	Porphyry	55' " " "	2.488

Xenoliths of basic rock in the porphyry.

As already stated, with an increase in acidification the dolerite is reduced to fragmental xenoliths, most of which are rounded, oval or irregular in outline. The following points may be summarised from a study of a large number of thin sections, many of which were cut to show xenolith margins.

Grain-size of xenoliths: (a) In the majority of sections the xenoliths are fine-grained and occasionally medium-grained as in the middle xenolithic zone; but they are rarely as coarse-grained as/

as the predominant basic member of the sill. However, in the Torr a' Bheannain intrusion a few large xenoliths (B.168a) show a similarity in grain-size with the associated dolerite. (b) In some specimens, especially from the middle xenolithic zone, different xenoliths in the same specimen show variation in grain-size. (c) Near the contact of the xenoliths with the porphyry there is no variation in grain-size suggestive of chilling.

Composition of Xenoliths: The xenoliths are mostly composed of felspar, iron-ore and pseudomorphs of augite; some show xenocrysts of quartz and felspar. Most of the minerals have undergone changes as a result of hybridization. Augite is altered to chlorite, fibrous uralite and carbonate, though occasionally relics of the original mineral can still be recognised. In some section such as B.116, B.132 pyrogenetic hornblende occurs (cf. p. 57). Felspars are invariably albitised. Occasionally the subophitic texture is retained (B.117 b). A few sections show some large laths of albitised felspar besides numerous small ones. Section B.Y. from the middle xenolithic zone is peculiar in showing a xenolith which is almost unchanged. Iron-ore exhibits the interesting change already referred to, i.e., becomes skeletal or rod-shaped. Biotite occurs as thin flakes often associated with chlorite. The abundance of apatite needles seen in the xenoliths provides interesting evidence of the selective fixation of mobile constituents/

constituents, a feature which has been stressed by Nockolds (1933). The xenocrysts of quartz usually have rims of altered augite; one section shows both hornblende and biotite in the rim.

In many sections the xenoliths have sharp contacts with the porphyry (Plate X, Fig. 4 and Plate V). In some they are irregular, a feature which becomes more and more accentuated until finally the xenoliths are reduced to small fragments. A very good example of such incorporation is provided by B.117 a. Here the augite which is represented by pseudomorphs occurs in two generations, the iron-ore is skeletal and the groundmass is composed of quartz and albitised felspar, along with a few flakes of biotite.

The effect of the incorporation of basic xenoliths is much less explicit in the acid rock than in the basic rock as a result of acidification (Nockolds, 1933). The following observations may be noted: (1) the contact is generally sharp, (2) there is no change in the coarseness of the intergrowth of micropegmatite in the vicinity of the xenolith, (3) biotite occurs as thin flakes, and (4) there are many druses of chlorite, calcite etc., in the porphyry enclosing the xenoliths in the middle zone.

An explanation for the relative poverty of biotite in the xenoliths and the acid rock even though the magma is potash-rich, is probably afforded by the observations of Endell that soda transfers more rapidly than potash into a lime-rich inclusion and potash in preference/

preference to soda if it is magnesia-rich. (Alling, 1936, p.256). Reference to the analysis of the basic rock in the Bennan area shows that it is lime-rich (hypersthene-dolerite; see Table VII, No. I).

Augite-granophyre.

Peculiar mixture rocks have already been described from three localities along the Struey burn (p.45). Two specimens collected from near the Cairn are similar to each other and appear to be more basic than the rock near the third waterfall in the Struey gorge. In the handspecimen all of them are light grey, medium-grained, non-porphyritic rocks with prisms of felspars and blades and patches of augite. In thin section, the rock is composed mostly of prisms of felspar, long blades of augite, iron-ore and apatite, set in a groundmass of micropegmatite and quartz (Plate X, Fig.1). The rock resembles in many respects the augite-diorite described in the Mull memoir (Thomas and Bailey, 1924, pp.218-9). The author has adopted the term augite-granophyre used by Harrison (1925, p.178).

Felspar occurs as short and stout rectangular prisms composed of both multiple-twinned plagioclase having low relief and small extinction angle (mid to basic oligoclase) and also untwinned orthoclase. All the grains have outer zones of turbid alteration recalling the corrosive effects of alkaline material referred to by the/

the authors of the Mull memoir (op.cit., p. 352). Micropegmatite fills the rectangular interiors of some felspar crystals (section B.128) and partially pseudomorphs many others. Most of them show undulose extinction. They all carry numerous needles of apatite.

Augite occurs in long colourless blades intimately associated with iron-ore. Some crystals are altered to hornblende, pleochroic from pale green to yellowish brown with extinction angle 20^{o}, and appear to be pyrogenetic and not secondary fibrous uralite. In section B.134 some of the long blades of augite are bent while others give the impression of radiating growth. The augite is sometimes enclosed in large plates of felspar. While discussing hybridization due to internal migration, Thomas describes these features as those exhibited by hybrids (Ardnamurchan memoir, 1930, p.101). Optic axial angle measured on the Federov stage is 51^{o} about Z and is not different from the optic axial angle of augite of the quartz-dolerites belonging to this area. This presumably implies that the composition of the two augites are not very different.

Iron-ore occurs in subhedral grains intimately associated with augite.

Apatite occurs conspicuously as long euhedral needles in the felspar and groundmass.

The groundmass is granophyric and is composed of micropegmatite. Quartz/

Quartz also occurs as individual grains. A few flakes of biotite occur and sometimes present basal sections. There are many small cavities filled with fibrous greenish pleochroic chlorite.

The specific gravity of this hybrid rock is 2.63. This value is intermediate between those of the porphyry (2.53) and the dolerite (2.77). The following table showshow the hybrid rock differs in mineral composition from the two end members (the values are expressed in volume percentages):

TABLE VI.

Rock.	Felspar (orthoclase and/ or plagioclase).	Mafic minerals.	Quartz.	Iron-ore.	Meso-stasic.	Apa-tite.
Porphyry.	18.0	0.60	6.2	3.3	71.9	Very little.
Augite-granophyre.	35.9	13.5	1.3	4.4	43.5	1.0
Hypersthene-dolerite.	35.7	28.8	2.3	4.7	28.1	Very little.

Tachylyte.

Thin veins of tachylyte similar to those of Drumaddon were found in the Struey gorge cutting the coarse dolerite. The tachylyte is composed of labradorite, both as numerous prisms and as a large number/

number of flow-oriented microlites set in a dark glassy groundmass. There are a number of chloritic pseudomorphs of a euhedral mineral which is probably pyroxene. Iron-ore can be recognised only under high power (x 400). Harrison describes a thin vein of tachylyte, 500 yards east of Struey burn (1925, p.178).

Dykes of later age.

The main intrusion at Bennan is cut by dykes of basalt porphyritic felsite (recorded by Harrison) and olivine-dolerite. The dykes are almost entirely confined to the west of the Black cave. No studies were made of the dykes.

MECHANICS OF INTRUSION.

From the foregoing account it is evident that the Bennan mass is a very complex body in its form, components and in the mutual relationships of its members. The history of intrusion must have been complex and hence elucidation of the sequence of events is difficult.

Along the Struey burn (Fig.6) the maximum complexity is attained and the intrusion consists of: (1) upper xenoporphyritic dolerite, (2) two thin bands of augite-granophyre, (3) a middle zone of xenoliths between two zones of xenolith-free porphyry, (4) another xenolithic zone, (5) a coarse-grained non-xenoporphyriti dolerite, (6) a zone of augite-granophyre, and (7) two sheets of fine/

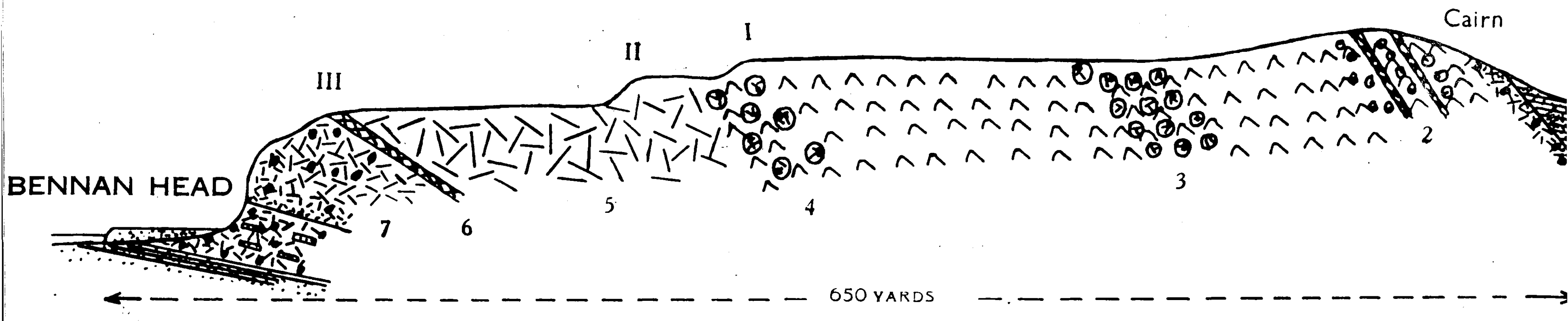


Fig. 6. Section along Struey Burn.

I, II, III, Waterfalls.

fine-grained basalt. A detailed study of the intrusions reveals many interesting facts which help in the elucidation of the intrusion mechanics.

(a) The xenoliths of the middle zone are fine-grained by comparison with the predominant basic member of the area. If the acid magma was emplaced along the planes of weakness of a thick basic dyke a quintiple dyke will be formed (Tyrrell, 1940, p.32). In such a case the central basic member represents the middle portion of the original basic dyke and hence will be at least as coarse as the flanking sheets. The conspicuous difference in grain-size between the middle zone of xenoliths and the flanking dolerites proves that the Bennan intrusion could not be the result of emplacement of the acid magma along the planes of weakness of a single basic dyke.

(b) The coarse-grained dolerite differs conspicuously from the quartz-dolerite member of the intrusion in being non-xenoporphyritic, as well as in grain-size. Hence it presumably constituted a separate intrusion.

(c) The presence of a chilled upper contact of a xeno-porphyritic basalt sheet with a lower basalt sheet in the Black cave (7 in Fig.6) suggests the possibility of more than one period of emplacement of the basic magma. (p. 46).

(d) The peculiar hybrid rock augite-granophyre, has been described by Harrison as due to slow cooling of a mixture of porphyry/

porphyry and dolerite. The complete absence of either xenocrysts of quartz, augite nodules, or xenocrysts of felspar, the long and bent form of the augite associated with iron-ore, and the nature of the felspars of the rock indicate strongly that the rock was the result of crystallization from a hybrid magma rather than from contact hybridization between a porphyry magma and basic rock. This view is further substantiated by a study of its chemical nature (p. 80). Along zones of contact hybridization, fresh augite is not developed. The position of the augite-granophyre in the Struey gorge where it occurs between the coarse-grained dolerite and the fine-grained tholeiite is inexplicable if the rock is assumed to be the result of contact hybridization. Hence the author considers that the augite-granophyre is the result of deep-seated hybridization

The porphyry is uniform throughout and there is no evidence to indicate more than one period of emplacement of the acid magma.

Hence, it can be concluded that though other parts of the Bennan intrusion are apparently simple, along the Struey burn there were at least three injections of basic magma, one of acid, and one of augite-granophyre.

Origin of xenoliths.

As already described, there are merging contacts between the flanking sheets of dolerite and the porphyry implying some degree of mixing. Associated with this phenomenon, there is the preservation/

preservation in the acid rock of fine-grained basic xenoliths in contradistinction to the medium-grain of the predominant basic member. In addition, most of the xenoliths show a sharp contact with the porphyry.

The xenoliths may be derived by any of the following ways:

(a) They could have been picked up prior to intrusion of the acid magma, the xenoliths representing chilled basic rock adhering to the country rock (cf. Smellie, 1912-15, p.125). This would naturally result in their haphazard distribution in the large volume of acid rock, but in the Bennan mass the xenoliths invariably occur near the merging contact between the porphyry and the dolerite.

(b) If the acid magma worked its way through the planes of weakness of the basic rock (Tyrrell, 1940, p.32), xenoliths of the latter could be preserved in the former due to incomplete incorporation. The difference in grain-size between the xenoliths and the basic rock as already described, is against this possibility.

(c) The xenoliths could be derived from the margins of two or more dolerite members which chill against one another; this would offer an explanation for the difference in grain-size noticed above. But studies of thin sections of specimens taken at close intervals from the dolerite-porphyry contact zone, do not show any variation in grain-size as the porphyry is approached/

approached as might be expected in such a case. Though the merging contact implies vigorous interaction between the acid magma and the basic rock, many of the xenoliths remain intact in shape; this may presumably be due to their fine-grained nature.

From the above discussion it is evident that a complete explanation of the origin of the xenoliths is difficult, but the third possibility suggests itself.

Classification of the Intrusion.

While discussing the nature of the contaminated complex dyke at Cape Neddick, Haff gives the following classification (1941, p. 839; also refer to p. 6 of this paper):

(a) Dykes differentiated in situ show (i) a lithologic gradation from basic to acid from the margin towards the centre and (ii) an absence of interior chilling.

(b) In composite dykes, intrusion of basic magma is followed after a short interval by acid magma into the central part of the former, which is partially liquid and (i) there is no internal chill of the acid component against the basic component and (ii) there is no lithologic gradation; but there is conspicuous contrast in composition between the members.

(c) Symmetrical multiple dykes: Intrusion of acid magma into any plane of a completely consolidated basic dyke: (i) there is no/

no lithologic gradation, (ii) the lithologic association is in many cases comparable to (b), (iii) the acid magma definitely chills against the basic flanks, and (iv) a symmetrical distribution of the components is not inherent, but where present is fortuitous.

(d) Symmetrical multiple dykes: Intrusion of acid dyke between two fully consolidated, contiguous dykes. Each of the three members show well defined chill selvages.

The Bennan intrusion shows the characters typical of composite intrusions (b), such as the absence of chilling of the acid component against the basic, and also a contrast in composition. It also appears to show characters attributable to type (d) such as the presence of fine-grained xenoliths in the acid rock which presumably represent the margins of consolidated basic members. However, the acid member is not chilled against the basic; on the contrary there is abundant mixing along the contacts. Thus it appears that though the Bennan intrusion shows many characters typical of composite intrusions, it also exhibits features which suggest a multiple relationship between basic members. The above discussion amply confirms Haff's warning that evidence based only on the absence of chill selvages must be interpreted with caution (op.cit., p.852).

Order/

Order of intrusion.

The basic magma was evidently the first to be emplaced since basic xenoliths are preserved in the acid rock. It is not clear whether the non-xenoporphyritic dolerite, which was presumably a distinct intrusion, was later or earlier than the xenoporphyritic dolerite. The basic magma was followed by the porphyry magma. Evidence already advanced shows that sufficient time elapsed for the consolidation of the basic magma, before the acid magma was emplaced. It is suggested that the hybrid augite-granophyre was injected last, though this is purely conjectural.

Dykes of later age.

As already stated, the Bennan mass is cut by a large number of N.W.-S.E. dykes of basalt, etc. It is interesting to note that they are comparatively few on the eastern side of the Bennan intrusion where the mass becomes upturned and assumes the form of a dyke.

COMPARATIVE STUDY OF THE INTRUSIONS.

It will be seen that the investigation of the above intrusions from Arran has emphasised a number of common features which are probably attributable to similar processes. In this section it is proposed to make a comparative study from three aspects, viz., (i) geological, (ii) petrological, and (iii) chemical, with a view to a petrogenetic interpretation.

(i) GEOLOGICAL DATA.

All the intrusions studied belong to the class of minor intrusions, either simple dykes as in Tormore and Cir Mhor or more complicated dykes acting as feeders to sills of similar nature as at Drumadoon, or a very complex body as at Bennan. They often stand out prominently owing to their greater resistance to weathering.

In all these intrusions there is the constant association of two contrasted rock-types: (1) fine- or medium-grained basaltic rock (the Bennan rock is coarser and is a dolerite) with (2) a coarsely porphyritic quartz-felspar-porphyry, a quartz-felsite or a pitchstone.

All the basic rocks studied are allogenic porphyries with xenocrysts of smoky quartz and dark grey felspar. The xenocrysts occur/

occur even in the chilled margins indicating their presence at the time of emplacement. Another point of interest is that the xenocrysts are comparable in size to the phenocrysts of the associated acid rocks (pp. 9, 15).

The acid rock, a porphyry as at Bennan and Drumadoon is normally grey but may vary in colour; in the latter area the porphyry is very dark grey at the base of the sill and light grey at the top. In Cir Mhor the central pitchstone shows a gradual passage to quartz-felsite. The thickness of both the basic and the acid members varies in dependance on the size of the intrusions being least at Tormore and greatest at Bennan. Judging from the areal distribution of the rocks, the acid member generally exceeds the basic in volume. Besides the basic and acid members, a hybrid rock was found at Bennan along the Struey burn.

In all these intrusions the basic member is always marginal and the acid central, a feature usually found in composite intrusions. They are mostly triple except at Bennan where the intrusion is multi-membered. The basic rock chills against the country rock but does not do so against the acid rock; the latter shows no chilling against the basic member.

The contact between the basic and acid rocks shows variations. It is rather sharp both in the No.II Tormore dyke and Drumadoon sill, but shows a slight amount of mixing in the Drumadoon/

Drumadoon dyke. In Bennan there is abundant mixing, the contact being a hybrid zone. Except in the simple Tormore dyke, the basic rock occurs also as xenoliths in the acid rock; this proves that the basic magma was the first to be emplaced, the acid following it.

(ii) PETROLOGICAL DATA.

The basic rocks of Tormore, Cir Mhor and Drumadoon are very similar to one another. They are tholeiites comparable in many respects to the tholeiites of Brunton type described from Mull; in Bennan the rock is a quartz-dolerite, comparable to Talaidh type of Mull, with or without hypersthene, the doleritic nature being due to coarser grain-size and the development of subophitic texture; but this texture is not alien to tholeiites of these intrusions. In all these rocks augite and felspar very commonly occur as scattered large phenocrysts, the former tending to form glomeroporphyritic aggregates. Orthopyroxenes occur in subordinate quantities either as pleochroic hypersthene as at Bennan, or very feebly pleochroic orthopyroxene probably enstatite as at Tormore, Cir Mhor and Drumadoon. The plagioclase of the tholeiites in the latter areas is more basic (acid labradorite) than at Bennan (basic andesine) and also shows a tendency to occur in crystals of many sizes presumably belonging to more than one generation. The groundmass of these tholeiites is either glassy or cryptocrystalline, the former being not so conspicuous as in the normal tholeiites of the dykes. Very/

Very often some irrregular grains of quartz are associated with the base. The groundmass of the quartz-dolerite of Bennan contains varying amounts of micropegmatite, associated with conspicuous amount of free quartz. Drusy cavities composed of carbonate, chlorite, free quartz and the cryptocrystalline groundmass are very common in the tholeiites; they are fewer in Bennan. These tholeiites differ from tholeiites occurring as single dykes, in the abundance of free iron-ore which is commonly occult in the latter.

All these rocks are xenoporphyritic with quartz and felspar. Quartz invariably shows augite rims and also has granophyric inclusions and in one case even zircon, very similar to the inclusions found in the quartz phenocrysts of associated acid rocks. The close similarity in size between the xenocrysts of quartz and felspar and phenocrysts of the same minerals has already been described. The possibility that the xenocrysts were incorporated from the acid rock by mixture at the contacts can be discounted since the xenocrysts are distributed haphazardly throughout the body of the rock and occur even in the chilled margin. Another possibility is that the crystals were contributed to the basic magma by the acid magma before the former's emplacement. This view has been expressed by several workers while trying to explain similar features elsewhere.

Harker/

Harker, describing the origin of xenocrysts in basalts from Skye, refers to those picked up prior to intrusion as 'antecedent' and those which were derived posterior to intrusion as 'consequent' (1904, pp. 220-223). Smellie found in south Bute that in the chilled contact of the basic rock, the xenocrysts of quartz showed clean margins while they had augite fringes away from it and therefore concluded that "the dolerite magma must have been impregnated by the acid magma with quartz and felspar immediately before intrusion." (1912-15, pp.130-131). Guppy and Hawkes come to a similar conclusion regarding the origin of the xenocrysts they describe from a composite dyke in eastern Iceland (1925, p.334). Regarding the xenocrysts in the Glasdrumman composite intrusion, Tomkeieff and Marshall conclude that they "were incorporated by the basalt magma prior to its intrusion." (1935, p.273). They describe as evidence the occurrence of xenoporphyritic basalt as single dykes a phenomenon similarly observed by Brögger in the Oslo area (op.cit., p. 274).

Although such single dykes have not been described from Arran, from the evidence already presented it can safely be concluded that the basic magma incorporated the xenocrysts prior to its emplacement. The process may be imagined as described by Hawkes (1924, p.112 and 1925, p.334). The basic magma caught up portions of the acid magma and incorporated them, being itself acidified in the process. The xenocrysts were then attacked, resulting/

resulting in the formation of augite rims round quartz and corrosion of felspars. This process of acidification of the basic magma explains the unusual features such as the presence of free quartz, micropegmatite and free iron-ore exhibited by the tholeiites and dolerites occurring as single dykes; this is more clearly brought out by a study of chemical analyses (p. 79). The sparser distribution of the xenocrysts in the basic rocks of these intrusions compared with the abundance of similar phenocrysts in the acid rocks, appears to be consistent with the slight acidification seen in the basic rock.

The augite rims round quartz xenocrysts are generally narrow in Drumadoon, Tormore and Cir Mhor, but broad in Bennan where resorption has often destroyed the quartz which is now represented by nodules of augite (compare Plate VIII, Fig.2 with Plate IX, Fig.2). This suggests longer and greater interaction between the xenocryst and the magma in Bennan probably because the magma had greater thermal energy. In none of these rocks does orthopyroxene form part of the augite rims round quartz, suggesting either that the interaction started only when most of the orthopyroxene had been made over into augite, the magma thus becoming effectively supersaturated with the latter or that the xenocrysts were incorporated only when the magma had reached that stage. The cracks invariably shown by the xenocrysts must be attributed to expansion by heat after their incorporation in the/

the basic magma as described by Harker (1904, p.220).

Xenocrysts of felspar whether they are orthoclase or oligoclase show varying degrees of corrosion. In the tholeiites of Drumadoon the rims of fresh felspar similar in composition to the plagioclase of the rock are more conspicuous than in Bennan.

The above study shows that the basic rocks of these intrusions present many similarities among themselves and the differences are presumably due to variation in the physical conditions associated with consolidation. They also show significant differences from the tholeiites occurring as dykes which must be attributed to their different consolidation history.

Except the basified porphyry the acid rocks of both Bennan and Drumadoon are mineralogically similar being coarsely porphyritic quartz-felspar-porphyries. The quartz phenocrysts of the Drumadoon porphyry are more euhedral than those of the Bennan mass implying less corrosion. Both the porphyries show pseudomorphs of pyroxene associated with iron-ore, zircon and apatite. The main difference between the porphyries of the two areas lies in the nature of the groundmass which is generally granophyric or sometimes micrographic as in Bennan whereas it is cryptographic in Drumadoon; this is probably due to the larger volume of the acid magma in the former area. The absence of crystallisation of any new mineral like biotite or hornblende in/

in the basified porphyry at Drumadoon also indicates that the magma possessed no excess thermal energy. In simpler intrusions the acid rock is a pitchstone and/or a quartz-felsite.(Tormore, No. II), the latter rock probably being a devitrified form of the former. Though all these are highly acid rocks as shown by the abundance of quartz etc., they show mafic minerals belonging to early stages in the reaction series like augite and microlites of hornblende (represented by pseudomorphs), in preference to mica.

The contact between the basic and acid rocks shows increasing complexity from Tormore to Bennan. There is very little mixing both at Tormore and in the Drumadoon sill, the phenomenon becoming more conspicuous in the Drumadoon composite dyke where the process is apparently more mechanical than chemical. The climax of contact hybridization processes is reached in Bennan where there is not only abundant mechanical mixing, but also conspicuous chemical interaction resulting in the formation of pyrogenetic hornblende and biotite together with the chloritization of augite.

(iii) CHEMICAL DATA.

In the accompanying tables the chemical analyses of the various rock types studied in this investigation with three new analyses/

analyses are tabulated for convenience as basic and acid rocks. Analyses of similar rock types from outside the areas studied are also given for purposes of comparison. Niggli values have been calculated for these analyses as also the norms according to the C.I.P.W. method.

Table VII shows clearly the relationship of the various basic members studied. The analyses reveal similarities with the Non-porphyritic Central Magma type of Mull (Memoir, 1924, p.17). The Niggli values of these rocks show that except the augite-granophyre, they are very similar, the difference being a slight richness of SiO_2 and Fe_2O_3 in Bennan. These minor differences must be attributed to local variations of conditions. They also show a distinct similarity with the tholeiites occurring as single dykes, from which they differ only slightly, being richer in SiO_2, K_2O, Al_2O_3 and poorer in FeO and TiO_2, features which must be attributed to pre-intrusive acidification of these tholeiites by the potash-rich acid magma (Table VIII, analysis II). Comparison with Niggli's type magmas also shows that the rocks differ from them, the nearest comparable type being si-gabbrodioritic type; but even here the rocks have a higher value for K than the type magma (Niggli, 1936, p.359).

A close examination of the analysis of the hybrid rock augite-granophyre, clearly brings out its unusual features.

Comparison/

Comparison with the analyses of both the dolerite and the porphyry at Bennan shows that it approximates to an acidified dolerite; although it is intermediate between the end members it is not strictly so. It shows an unusually high percentage of TiO_2 and P_2O_5, these constituents being higher than in either the basic or acid rock. The occurrence of numerous large needles of apatite would account for the P_2O_5. TiO_2 is probably present intimately associated with the iron-ore and in the pyroxene. In this connection the comments made by Thomas and Smith on the richness of these two oxides while discussing an increase in TiO_2 in the quartz-diorite stage of the hybrid rocks in Cotes Du Nord region in France that "both phosphoric and titanic acids may be presumed to have travelled with the highly acid or volatile residuum of the consolidating magma" are relevent (1932, p.289).

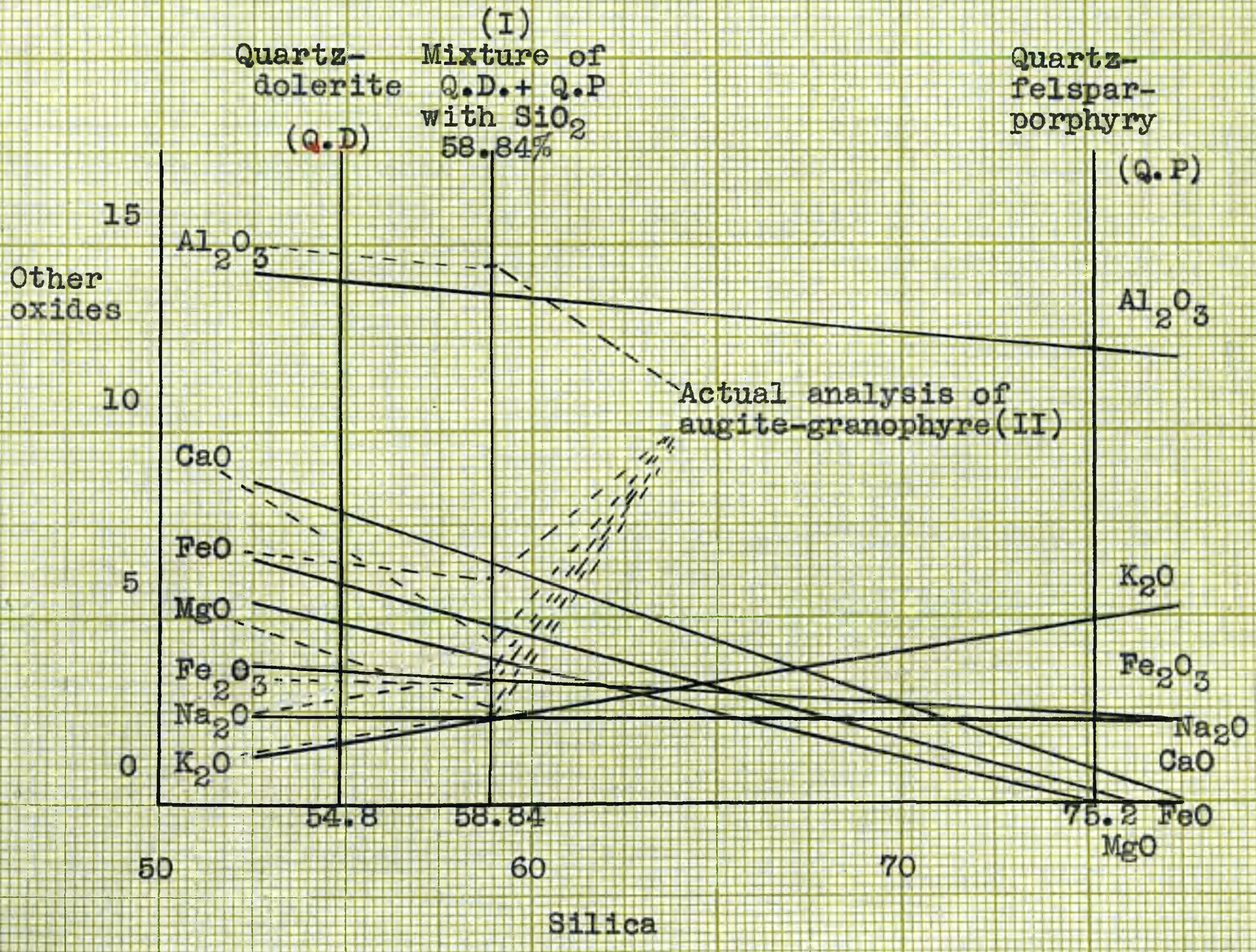
Since the augite-granophyre is presumably the result of crystallisation from a hybrid magma (p. 66) resulting from the interaction of basic and acid magmas the accompanying silica-oxide diagram (Fig.7) helps to elucidate this mutual relationship. The oxide values have been plotted for the dolerite and the porphyry on the assumption that they represent the nearest equivalents to the original magmas. This enables a comparison between a theoretical mixture of the two end members with the same silica percentage as the actual hybrid rock. The study brings out clearly that the theoretical mixture and the actual hybrid/

Fig. 7

	I	II
SiO_2	58.84	58.84
Al_2O_3	13.80	14.43
Fe_2O_3	3.35	3.31
FeO	4.75	6.12
MgO	3.80	2.68
CaO	6.50	4.43
Na_2O	2.30	3.61
K_2O	2.30	2.38

I Composition of theoretical mixture of quartz-dolerite and quartz-felspar-porphyry with silica 58.84 %

II Actual analysis of augite-granophyre.



hybrid are very different, showing discrepancies for values of most of the oxides. Augite-granophyre has a higher value for Al_2O_3, FeO and Na_2O and a lower value for CaO and MgO than the theoretical mixture. Only the values for K_2O and Fe_2O_3 appear to agree rather closely. Therefore it is obvious that the hybrid rock could not be the result of a simple mixture of the end members and the process must have been of a complex character. In other words the system was not a closed one and there must have been scope for removal and addition of material. The augite-granophyre is thus not a straight-line compositional variant of the basic and acid magmas. It represents a rock formed by the interaction of a metasomatised product of the basic magma with the acid magma, the process presumably taking place at depth. Harker has emphasised this point in his discussions regarding the nature of hybrid rocks in general (1900, 1904).

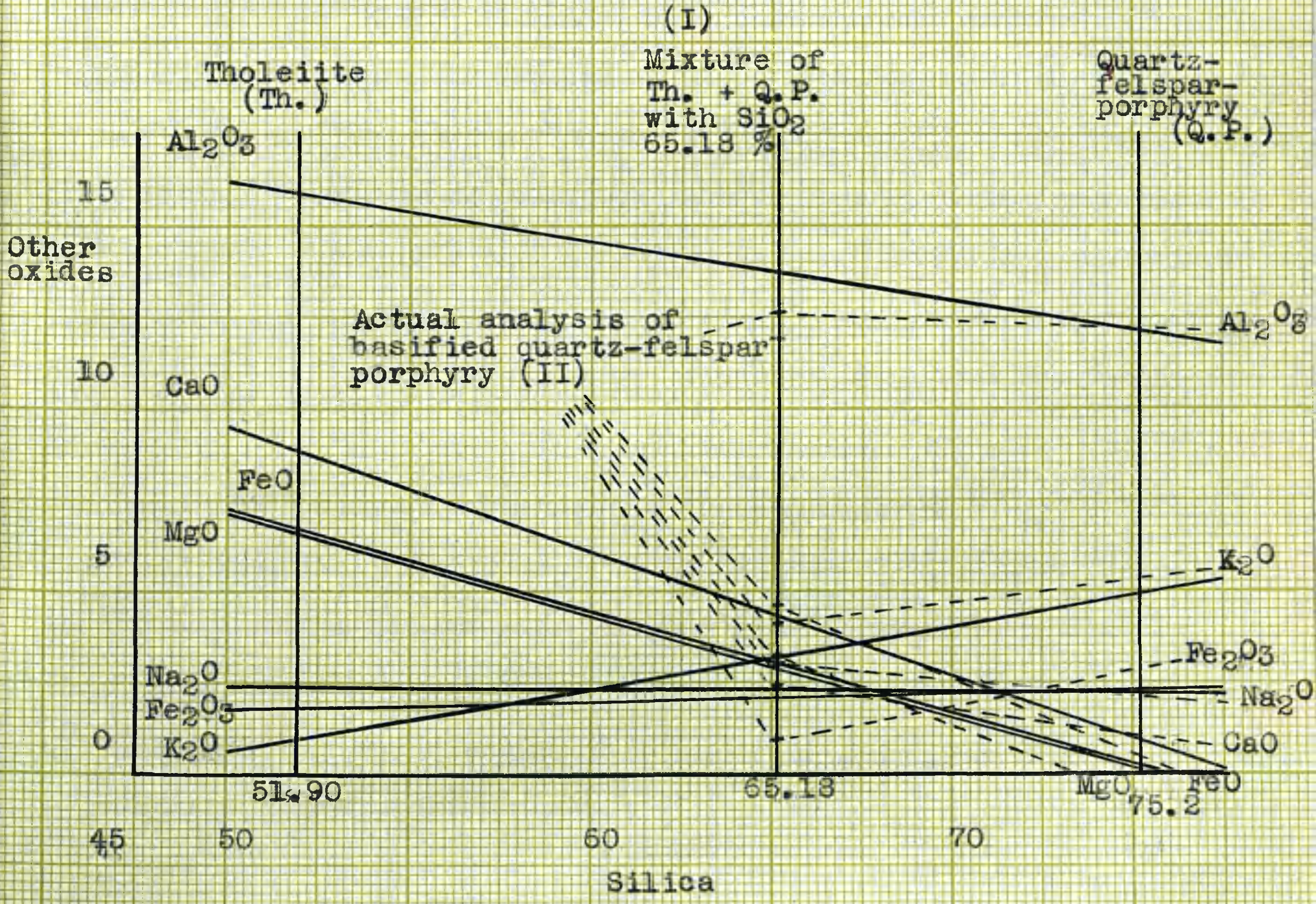
Table VIII (acid rocks) shows that the Bennan porphyry has a high percentage of silica. It is rich in potash which is in excess of soda. It also shows an unusual richness of Fe_2O_3. In view of the close petrographic similarity between the uncontaminated porphyry from Drumadoon and the Bennan porphyry, an analysis was not made. The analysed specimen D.30 which is the contaminated hybrid porphyry, is of variable character and the distribution of the xenoliths highly irregular. Variations are observed even in a single thin section (p. 31). Furthermore, the/

Fig. 8

	(I)	(II)
SiO_2	65.18	65.18
Al_2O_3	13.75	12.57
Fe_2O_3	2.10	0.92
FeO	3.00	4.63
MgO	2.80	3.22
CaO	4.30	2.48
Na_2O	2.25	2.86
K_2O	3.20	4.09

I Composition of theoretical mixture of Drumadoon tholeiite (sill) and Bennan quartz-felspar-porphyry with silica 65.18 %

II Actual analysis of basified quartz-felspar-porphyry from Drumadoon sill.



the mafic minerals of the xenoliths are partially altered. In view of this the analysis is of less value, though certain features emerge from a comparison of the analysis with the analyses of the Bennan porphyry and the Drumadoon tholeiite. The basified porphyry has a lower silica value and a higher value for FeO, MgO, and CaO, compared to the Bennan porphyry. By plotting a silica-oxide diagram similar to Fig. 7, the relationships are very well brought out (Fig.8). The actual analysis shows considerable variations from a theoretical mixture of the end members with the same percentage of silica suggesting that selective processes were also in operation, though from the petrographic account the incorporation of basic rock appears to be more mechanical than chemical (p. 32). The Bennan porphyry compares closely with the granophyric granite of the Central Ring Complex in Arran, and hornblende-granophyre from Skye. Comparison with Niggli's type magmas again shows that the porphyry differs from them, the nearest comparable type being aplite-granite but the Bennan rock shows an excess value for 'fm' as a result of basification (Niggli, 1936, p.358).

The pitchstone of Judd's No. II dyke and also that of Cir Mhor show an excess of soda over potash, a feature expressed in their mineralogy (the felspar phenocrysts are mostly basic oligoclase). The former rock shows an unusual richness in FeO CaO and water. The richness of FeO can be accounted for by the presence/

presence of iron-olivine fayalite, the lime going mainly to form pyroxene. The richness in water of pitchstones is very well known. The rock also differs from Niggli's type magmas.

To sum up, a study of the chemistry of the rocks belonging to these intrusions shows that (a) rocks of corresponding types show analogies in the different bodies, (b) they can be compared rather closely with rocks from other areas of the British Tertiary Igneous Province (Skye, Mull etc.) and, (c) they show certain unusual characters resulting from deep-seated hybridization.

TABLE VII.

BASIC ROCKS.

	I	II	III	IV	V	VI	VII	VIII	IX
SiO_2	54.83	58.84	51.90	54.52	53.97	54.11	51.63	51.53	55.79
Al_2O_3	14.10	14.43	15.78	14.53	14.65	11.65	11.77	11.05	15.97
Fe_2O_3	3.57	3.31	1.83	2.21	3.62	2.76	3.23	2.73	12.50
FeO	5.87	6.12	6.64	6.06	6.32	7.02	10.47	10.98	-
MnO	0.37	0.26	0.19	0.24	0.30	0.21	0.35	0.45	-
MgO	4.88	2.68	6.54	5.61	4.49	5.30	5.02	5.21	2.22
CaO	7.90	4.43	8.78	8.08	7.98	8.77	9.34	9.68	7.06
Na_2O	2.32	3.61	2.46	3.66	2.54	2.63	2.90	3.48	2.21
K_2O	1.73	2.38	0.95	1.14	1.52	1.75	0.91	0.86	1.86
H_2O (+105°)	1.23	1.75	1.02	0.93	0.94	0.81	1.40	1.26	Ign. 2.43
H_2O (-105°)	0.48	0.88	2.05	1.95	1.92	0.68	0.68	0.71	
TiO_2	0.74	1.14	0.76	0.87	1.24	3.37	2.00	1.57	-
P_2O_5	0.24	0.31	0.05	0.21	0.27	0.58	0.29	0.22	-
CO_2	1.90	-	0.97	-	0.51	0.05	0.11	0.08	
	100.19	100.14	99.92	100.04	100.40	99.97	100.25	100.07	100.49

Niggli Values.

	I	II	III	IV	V	VI	VII	VIII
si	155.7	195.4	134.5	148.6	151.5	150.33	131.2	128.2
qz	+18.22	+29.24	+3.38	+2.2	+13.1	+9.65	-3.56	-10.6
al	23.52	28.29	24.11	23.20	24.24	19.00	17.68	16.27
fm	43.10	39.65	43.70	41.66	42.08	44.33	48.17	48.20
c	24.02	15.73	24.42	23.53	24.07	26.17	25.46	25.81
alk	9.37	16.54	7.78	11.60	9.60	10.17	8.69	9.70
k	0.33	0.30	0.20	0.17	0.28	0.28	0.18	0.14
mg	0.48	0.34	0.58	0.55	0.45	0.50	0.40	0.40

Norms.

	I	II	III	IV
Quartz.	13.86	13.86	5.28	4.26
Orthoclase.	10.01	13.90	5.56	6.67
Albite.	19.39	30.39	20.96	30.92
Anorthite.	23.07	16.40	29.19	19.74
Salic group.	66.33	74.55	60.99	61.59
Diopside.	2.04	3.00	6.55	15.36
Enstatite.	11.60	6.00	14.40	9.30
Iron metasilicate.	7.00	6.34	8.58	5.41
Magnetite	5.10	4.87	2.55	3.25
Ilmenite.	1.37	2.13	1.52	1.67
Apatite.	0.57	0.73	0.12	0.51
Calcite.	4.30	-	2.20	-
Femic group.	31.98	23.07	35.92	35.50

I. (24457 Lab.No.826) Hypersthene-dolerite, basic member of Bennan composite sill, shore at foot of Struey falls, Bennan Head, Arran.

Analyst: E.G.Radley.

II. (B.131) Augite-granophyre, hybrid rock near Cairn, along Struey Burn, west of East Bennan farm.

Analyst: W.H.Herdsman.(new analysis).

III. (D.24) Tholeiite, Drumadoon, Lower dolerite; very near contact with the acid rock (near the southern end in the cliffs).

Analyst: W.H.Herdsman.(new analysis).

IV. (25622 Lab.No.853) Tholeiite (Brunton type), basic member of composite pitchstone-tholeiite dyke, Judd's No. II dyke.

Analyst: E.G.Radley.

V. (17170 Lab.No.432) Tholeiite, Talaidh type, basic margin of composite sill, Ruadh a' Chromain, Mull.

Analyst: E.G.Radley.

VI. (23845 Lab.No.800) Andesitic tholeiite, 60' North West dyke, a continuation of the Acklington-Handwick dyke.

Analyst: B.E.Dixon.

VII. (S.16809) Tholeiite of Brunton type; Tertiary dyke. On shore $\frac{1}{4}$ mile N. of Kintallen, 3 miles N.N.W. of Salen, Mull.

Analyst: E.G.Radley.

VIII. (S.16810) Tholeiite of Brunton type; Tertiary dyke. On shore $\frac{1}{4}$ mile E. of Arla, $5\frac{1}{2}$ miles S.E. of Tobermory, Mull.

Analyst: E.G.Radley.

IX. Augite-andesite, the exterior member of Cir Mhor composite dyke, Arran.

Analyst: J.A.Schofield.

TABLE VIII.

ACID ROCKS.

	I	II	III	IV	V	VI
SiO_2	75.22	65.18	76.65	71.51	71.98	72.37
Al_2O_3	12.22	12.57	11.89	10.55	13.13	11.64
Fe_2O_3	2.30	0.92	1.19	0.79	1.33	1.42
FeO	0.22	4.63	1.02	2.22	1.64	1.08
MnO	0.25	0.08	0.26	0.42	0.14	-
MgO	0.06	3.22	0.15	0.52	0.56	0.52
CaO	0.84	2.48	0.91	1.52	1.15	1.30
Na_2O	2.22	2.86	3.44	4.12	2.98	4.15
K_2O	4.94	4.09	4.26	3.48	4.93	3.98
H_2O (+105°)	0.52	0.72	0.40	4.07	1.38	ign. 4.86
H_2O (-105°)	0.72	0.85	0.41	0.19	0.39	
TiO_2	0.28	0.24	0.28	0.33	0.37	-
P_2O_5	0.18	0.07	0.16	0.24	0.19	-
CO_2	0.03	1.93	0.09	-	-	-
	100.00	99.84	100.16	100.04	100.18	101.32

Niggli Values.

	I	II	III	IV	V
si	480.5	261.7	467.0	405.5	393.4
qz	+243.1	+ 74.9	+217.4	+165.4	+162.28
al	45.98	29.64	43.33	35.38	42.30
fm	14.18	38.08	13.33	20.41	18.03
c	5.75	10.60	5.93	9.19	6.89
alk	34.10	21.69	37.41	35.03	32.78
k	0.60	0.49	0.45	0.36	0.52
mg	0.54	0.51	0.11	0.22	0.25

Norms.

	I	II	IV
Quartz.	41.28	23.46	30.66
Orthoclase.	29.47	24.46	20.57
Albite.	18.86	24.10	34.58
Anorthite.	2.78	5.56	0.28
Corundum.	2.14	1.33	-
Salic group.	94.53	78.91	86.09
Enstatite.	0.20	5.90	0.70
Iron metasilicate.	-	7.39	1.85
Diopside.	-	-	4.77
Magnetite.	0.70	1.39	1.16
Hematite.	1.76	-	-
Ilmenite.	0.61	0.46	0.61
Apatite.	0.44	0.17	0.57
Calcite.	0.10	-	-
Dolomite.	-	4.05	-
Femic group.	3.81	19.36	9.66

I. (24460.Lab.No.829) Quartz-felspar-porphyry, acid member of Bennan composite sill, quarry half a mile W.S.W. of Levencorroch, Arran.

Analyst: E.G.Radley.

II. (D.24) Basified quartz-felspar-porphyry, Drumadoon; sill in the Doon, taken from ten feet above the tholeiite-porphyry contact.

Analyst: W.H.Herdsman (new analysis).

III. (24454 Lab.No.824) Granophyric-granite of Central Ring Complex, quarry in Allt nan Dris, 1000 feet north of Derenenach, Arran.

Analyst: E.G.Radley.

IV. (25621 Lab.No.852) Pitchstone with ortho-and clino-pyroxenes and olivine Judd's No. II dyke, Tormore shore

Analyst: E.G.Radley.

V. (7064) Hornblende-granophyre, Beinn a' ahairn, 3½ miles south by west of Broadford, Skye.

Analyst: W. Pollard.

VI. Porphyritic-pitchstone, centre of Cir Mhor dyke.

Analyst: E.C. Thomson.

MECHANICS OF INTRUSION.

The intrusions studied in this investigation reveal an increasing complexity from the simple dykes of Tormore shore to the complex mass at Bennan presumably brought about by differences in the volumes of the magmas and their thermal characters at the time of their emplacement. The role played by volatiles is not clear in view of the possibility of escape from the magma systems.

The Cir Mhor and Tormore (No.II) composite dykes represent the simplest of these intrusions, where the basic magma filled a narrow fissure and was followed by a greater volume of acid magma which presumably solidified first as a pitchstone and devitrified later into quartz-felsite. At Drumadoon the triple composite dyke consolidated in an elongated and sinuous fissure and at one point served as a feeder to the composite sill. There was greater mixing in the composite dyke between the acid magma and the basic rock due to the higher energy possessed by the former during its emplacement in the dyke; this energy necessarily diminished in the sill. The occurrence of a xenoporphyritic tholeiite along what is probably the fault plane in the sill presumably indicates a recurrence of intrusion of the basic magma. The sequence in the whole series appears to be basic-acid-basic, resembling the sequence noted by Tomkeieff and Marshall among dykes (1935, p.283).

The Bennan intrusion represents the climax of these phenomena/

phenomena. There were presumably at least three injections of basic magma, and one of the acid magma. The volume of the magmas emplaced was larger than in the other areas described. The acid magma apparently had greater energy as shown by the high degree of contact hybridization with the already consolidated basic magma. The suggested emplacement of the hybrid as the last in the series would indicate a sequence of basic-acid-acidified basic.

PETROGENESIS.

In all these intrusions there is the constant association of two contrasted rock types, a feature similar to many such intrusions described from Skye, Mull, etc., which points to the association and simultaneous availability of both acid and basic magmas. These intrusions do not show any intermediate rock types either in the chemical or petrographical sense, that would be the result of a process of progressive crystallisation-differentiation of a parent basalt magma as advanced by Bowen (1928). The petrological and chemical nature of the augite-granophyre of Bennan also reveal that it is not formed from crystallisation-differentiation but is a product of crystallisation from a hybrid-magma. The basic and acid rocks themselves show unusual features in their chemistry and mineralogy. Petrological and chemical data already presented (pp.77,79,82) show clearly that the/

the original basic and acid magmas have been modified by each other to a slight but significant extent.

The ultimate origin of the two magmas has been the crux of many petrological problems, especially in the British Tertiary Igneous Province. According to Thomas and Bailey the magmas were brought about by "magmatic differentiation through remelting of fallen crystals at lower levels (1924, p.33). Holmes explains it on the basis of the refusion or palingenesis of the acid and basic layers of the crust by radioactive heat (1931, p.242). Nockolds believes that differentiation in intercrustal magma basin yields two contrasted magma types by 'contrasted differentiation' as opposed to progressive differentiation (1934). In a discussion on "the association of granite and dolerite in igneous bodies," Krokström supports the refusion theory of Holmes, basing his conclusions on petrological and petrochemical evidence from his study of the Breven dyke in Sweden. He considers that the Breven granophyre is a product of refusion or a 'rheomorphic rock.' (1937, p.275).

A final answer to this fundamental problem of petrology is beyond the scope of this limited investigation and can only come by an elaborate and comparative study of all aspects of such associations which are so characteristic of the Tertiary Igneous Province.

AGE OF THE INTRUSIONS.

All the intrusions described in this paper have been emplaced into Keuper marls and sandstones and therefore are post-Triassic in age. They are all cut by numerous dykes of olivine-dolerite, tholeiite, quartz-dolerite etc., which are known to be Tertiary in age by their similarity with other dykes both in Arran and in the west of Scotland. Hence these composite and multiple intrusions are earlier than some of the Tertiary dykes. Since the Mesozoic was an era of comparative igneous quietude, the age of these intrusions must be Tertiary.

The place occupied by composite intrusions in the sequence of igneous activity which developed in the Brito-Icelandic province during Tertiary times has been described briefly in the Arran memoir (1928, pp.111-2). In Arran first in the sequence was the emplacement of undersaturated magma as sills of crinanite and olivine-dolerite especially in the south-east of the island. This was followed by the second phase when there was extensive intrusion of over-saturated magma as plutonic masses in the central area, as also sills of quartz-dolerite. The acid magma developed an explosive phase probably represented by the agglomerate in the Central Ring Complex and there was the phenomenon of composite intrusions as sills and hybrid mixtures. Harker's remark while discussing the position of composite intrusions/

intrusions in Skye that "they belong to a point of time accurately separating the plutonic phase from that of the minor intrusions and marks the final stage of a volcanic epoch"(1904, p.425) may be equally well applied to these intrusions in Arran.

During the final phase of Tertiary activity there was large scale development of dykes. The evidence from mapping at Drumadoon shows that the olivine-dolerites were the first, followed by quartz-dolerites and tholeiites, and finally felsite. This supports Tyrrell's remarks that "in this late magmatic recurrence the evidence thus clearly points to the same succession of undersaturated by oversaturated magma, as was observed between crinanite sills and the sills of the quartz-dolerite series." (op. cit., p.251).

In the North Arran memoir Harker refers to an interesting point that "the peculiar conditions which determine the almost simultaneous intrusion of basic and acid rocks have been realised in two distinct epochs," in Arran. (1903, p.116). Attention has been previously drawn to the similarity of grain-size of the xenocrysts and phenocrysts (p. 74). In the Tormore shore No. II dyke shows small xenocrysts similar to those of the associated quartz-felsite. Within a quarter of a mile at An Cumhann the xenocrysts are large corresponding to those of the porphyry. The absence of any mixing of the two rock types as revealed by a mixture of xenocrysts of different sizes in the basic rock or phenocrysts of different sizes in the acid rock appears to support Harker's view.

SUMMARY AND CONCLUSIONS.

This investigation consists of detailed studies of the geology and petrology of some igneous intrusions from (i) Tormore shore and Cir Mhor, (ii) Drumadoon, and (iii) Bennan, in the Island of Arran. A comparative study of all these intrusions brings out salient features which lead to some general conclusions.

The author's revision of Judd's famous work on the composite intrusions shows many differences in mapping. The petrography of the rock-types is described and their nomenclature revised. According to modern definitions it is shown that only Judd's No. II dyke and Cir Mhor dyke can be described as composite. Judd's No. I dyke is a multiple dyke (an additional band of tholeiite on the west is described) and Judd's No.III dyke actually consists of two different dykes.

A detailed study of the composite dyke and sill at Drumadoon shows that (i) both the upper mass at the Doon and the lower mass on the shore at Drumadoon Point were originally parts of the same sill and that their present relative positions are the result of an east-west fault. It is presumed that along this fault line there was a recurrence of emplacement of the basic magma. (ii) The composite dyke which runs from Drumadoon Bay to Cleiteadh nan Sgarbh and the similar dyke seen at/

at An Cumhann are parts of the same dyke. (iii) Geologically and petrologically the dyke is related to the sill and was presumably the feeder of the sill. (iv) The dyke exhibits a greater amount of mechanical mixing between the acid and basic members than the sill due to differences in thermal energy possessed by the magma according to its emplacement habit. The dark grey porphyry of the sill is the result of basification by the predominantly mechanical incorporation by the acid magma of the basic rock.

A study of the Bennan intrusions showsthat (i) the dyke-like Torr a' Bheannain mass is similar to the dyke-like mass of Creag Dhubh, (ii) the thin N.W.-S.E. mass between these two is composed of xenoporphyritic tholeiite, and (iii) another N.W.-S.E. mass N.E. of Smithy is actually a part of the Bennan mass. It is shown that the main Bennan intrusion is a complex body, probably laccolithic along the Struey burn and dyke-like in the east along Creag Dhubh. A detailed study of the Struey burn section shows that here the intrusion is complex and is composed of two sheets of tholeiite in the south, a coarse dolerite, a median xenolithic zone and three zones of a hybrid rock, augite-granophyre. It is postulated that the Bennan complex is the result of at least three phases of intrusion of basic magma together with one of the acid and one of the hybrid magmas. Though the Bennan intrusion in general appears to be composite/

composite, a study of the xenoliths of basic rock in the acid rock indicates that the basic members were fully consolidated when the acid magma was emplaced and were probably multiple in their mutual relationship.

A comparative study of all the intrusions is made from the geological, petrological and chemical aspects which emphasises the great similarities in the corresponding rock types in addition to the evident variation in complexity from the simple dykes of Tormore shore (No.II) to the highly complex Bennan intrusion. The constant association of basic and acid rocks and the development of hybrid rocks of unusual character due to deep-seated hybridization are discussed. The present studies lend further support to current views regarding the association of basic and acid magmas, features which do not accord with the view of a progressive crystallisation-differentiation of a basaltic parent magma as advanced by Bowen.

A C K N O W L E D G M E N T S

The author's heartfelt and sincere thanks are due to Dr.G.W.Tyrrell, Department of Geology, University of Glasgow, for suggesting the problem, for his guidance in the course of the work from a life-long study of Arran Geology and Petrology and for placing at the disposal of the author his own collection of rock-slides; to Dr. B.C. King of the Department for his help and constructive criticism of the paper; to Mr. A.R. Ferguson for the skilful preparation of a large number of thin slides and the invaluable help rendered in the photographic work for the investigation; to Dr. A.T.J. Dollar of the Department for kindly lending for use his own Integrating Micrometer; to the Director, H.M. Geological Survey for kindly lending the relevant rock-slides for comparison; and finally to the Government of India for the grant of a generous scholarship which enabled the author to undertake the investigation in this country.

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EXPLANATION OF PLATES I - X.

Plate I. A close up view of the upper tholeiite of the down-faulted region of the Drumadoon sill on the shore at Drumadoon Point. The photograph shows the tholeiite hading to the east at 20°-40°. The main sill can be seen in the background.

Plate II. A close up view of the lower contact of the Drumadoon sill in the cliffs showing horizontal sediments, lower tholeiite, and the dark porphyry enclosing xenoliths of the basic rock.

Plate III. A section across the composite dyke at Cleiteadh nan Sgarbh showing the porphyry, a thin dyke of fine-grained quartz-dolerite, tholeiite and banded felsite.

Plate IV. A view of the Black Cave, Bennan Head, showing a raft of sediment enclosed in the xenoporphyritic basalt.

Plate V. A cut and polished handspecimen from the middle zone of xenoliths. Notice the sharp contact of the porphyry and the xenoliths.

Plate VI.

Fig.1. T.1. Tholeiite. Eastern band, Judd's No.I dyke, Tormore shore. X45. Polarised light.

Labradorite laths subophitic with augite. Dark glassy groundmass. In the centre an ocellus-like vesicle.

Fig.2. T.17. Southern band of xenoporphyritic tholeiite. Judd's No. II dyke, Tormore shore. X45. Polarised light.

Phenocrysts and laths of labradorite, granular augite and irregular grains of iron-ore. Xenocryst of quartz with augite rim and a xenocryst of felspar with a dark corroded interior and a rim of fresh felspar.

Fig.3. Ar.201. Quartz-felsite. Judd's No. II dyke, Tormore shore. X45. Crossed nicols.

Phenocrysts of oligoclase and a phenocryst of quartz. Micropegmatitic groundmass (coarse intergrowth between quartz and alkali-felspar).

Fig.4/

Plate VI.

Fig.4. Ar.202. Pitchstone. Judd's No. II dyke, Tormore shore. X45. Polarised light.
Phenocrysts of felspar, augite associated with iron-ore and microlites of hornblende. Glassy base. An irregular vescicle with cryptocrystalline material, in the centre.

Plate VII.

Fig.1. T.24. Olivine-dolerite. Judd's No. III dyke, Tormore shore. X45. Polarised light.
Labradorite laths, ophitic and subophitic with titanaugite. Pseudomorph of olivine composed of serpentine and iron-ore can be seen.

Fig.2. Ar.189. Xenoporphyritic tholeiite. Outer member of the Cir Mhor composite dyke, E. flank. X45. Polarised light.
Labradorite laths and granular augite. A phenocryst of felspar and a xenocryst of quartz with an augite rim.

Fig.3. Ar.187. Pitchstone. Central member of Cir Mhor dyke, E. flank. X45. Polarised light.
Phenocryst of felspar (with cracks), microlites of hornblende and crystallites with fern-like growths; in the centre, a circular vescicle with radiating microlites. Glassy groundmass.

Fig.4. Ar.188. Quartz-felsite. Intermediate member of Cir Mhor dyke, E. flank. X45. Crossed nicols.
Phenocrysts of oligoclase and a corroded phenocryst of quartz. Micropegmatitic groundmass.

Plate VIII.

Fig.1. D.2. Xenoporphyritic tholeiite. 1½ ft. from the upper surface of the upper basic member of the down-faulted sill on the shore at Drumadoon Point. X20. Polarised light.
Labradorite laths, granular augite and a xenocryst of subhedral quartz with rounded inclusions of cryptocrystalline material and surrounded by a narrow rim of augite. Bundles of laths and microlites of felspar can be seen.

Fig.2/

Plate VIII.

Fig.2. D.4. Tholeiite--Quartz-felspar-porphyry contact. Down-faulted sill on the shore at Drumadoon Point. X20. Polarised light.

Zig-zag contact. On the porphyry side of the contact (left), a xenocryst of quartz with narrow rim and a corroded xenocryst of felspar. The porphyry also shows phenocrysts of quartz unaffected by basification.

Fig.3. D.22. Xenoporphyritic tholeiite with a vein of tachylyte. Lower member of the Drumadoon sill at the base in the cliffs. X20. Polarised light.

The tholeiite shows a felspar xenocryst with a dark corroded interior and an outer rim of fresh felspar. Vein of tachylyte with a large phenocryst and numerous prisms of labradorite. Dark glassy groundmass.

Fig.4. D.9 Quartz-felspar-porphyry. Down-faulted region at Drumadoon Point. X20. Polarised light.

Phenocrysts of felspar and quartz. A dark pseudomorph of pyroxene in the centre. Cryptocrystalline groundmass.

Plate IX.

Fig.1. D.63. Acidified tholeiite. An Cumhann, near Tormore shore (N.W. of the dyke). X20. Polarised light.

Acidification shown by an increase in the amount of quartz and micropegmatite. Part of the section is undigested xenolith (lower portion).

Fig.2. B.16 Quartz-dolerite. Upper member near Creag Dhubh quarry (western side). X20. Polarised light.

A xenocryst of quartz with a broad rim of radiating prisms of augite. The dolerite shows prisms of plagioclase and granular or subophitic augite.

Fig.3. B.31. Quartz-dolerite. Upper member, east of Cairn; 8 ft. south of the outer margin. X45. Polarised light.

A xenocryst of felspar showing the effects of corrosion. Notice the skeletal iron-ore, augite etc., within the felspar. Basic andesine laths subophitic with augite (upper portion).

Fig.4./

Plate IX.

Fig.4. B.126. Coarse quartz-dolerite. Struey gorge near the second waterfall. X45. Polarised light.
Labradorite prisms subophitic with augite, and irregular grains of iron-ore. Micropegmatitic groundmass. Numerous apatite needles.

Plate X.

Fig.1. B.131. Augite-granophyre. About 30 ft. south of Cairn. X45. Polarised light.
Prisms of felspar and long blades of augite associated with iron-ore. Micropegmatitic groundmass. Needles of apatite.

Fig.2. B.74 (a). Basified porphyry. Lower member, 39 ft. from contact with sediment, 1 mile east of Black Cave, in the cliffs. X20. Polarised light.
Rock rich in mafic constituents. Xenocryst of quartz with a rim of augite besides a phenocryst of felspar with a corroded outline. There is a large phenocryst of felspar pseudomorphed by micropegmatite, to the left.

Fig.3. B.74(a). X165. Crossed nicols.
Magnified view of a phenocryst of felspar whose outer margin is pseudomorphed by micropegmatite.

Fig.4. B.X. Middle zone of xenoliths. Along Struey burn. X20. Polarised light.
A highly digested xenolith (right) with a sharp contact with the porphyry.

Plate XI. Geological map showing the Drumadoon intrusions and the Dykes of Tormore shore (six inch scale).

Plate XII. Geological map of the Bennan Intrusions (six inch scale).

PLATE I

PLATE II

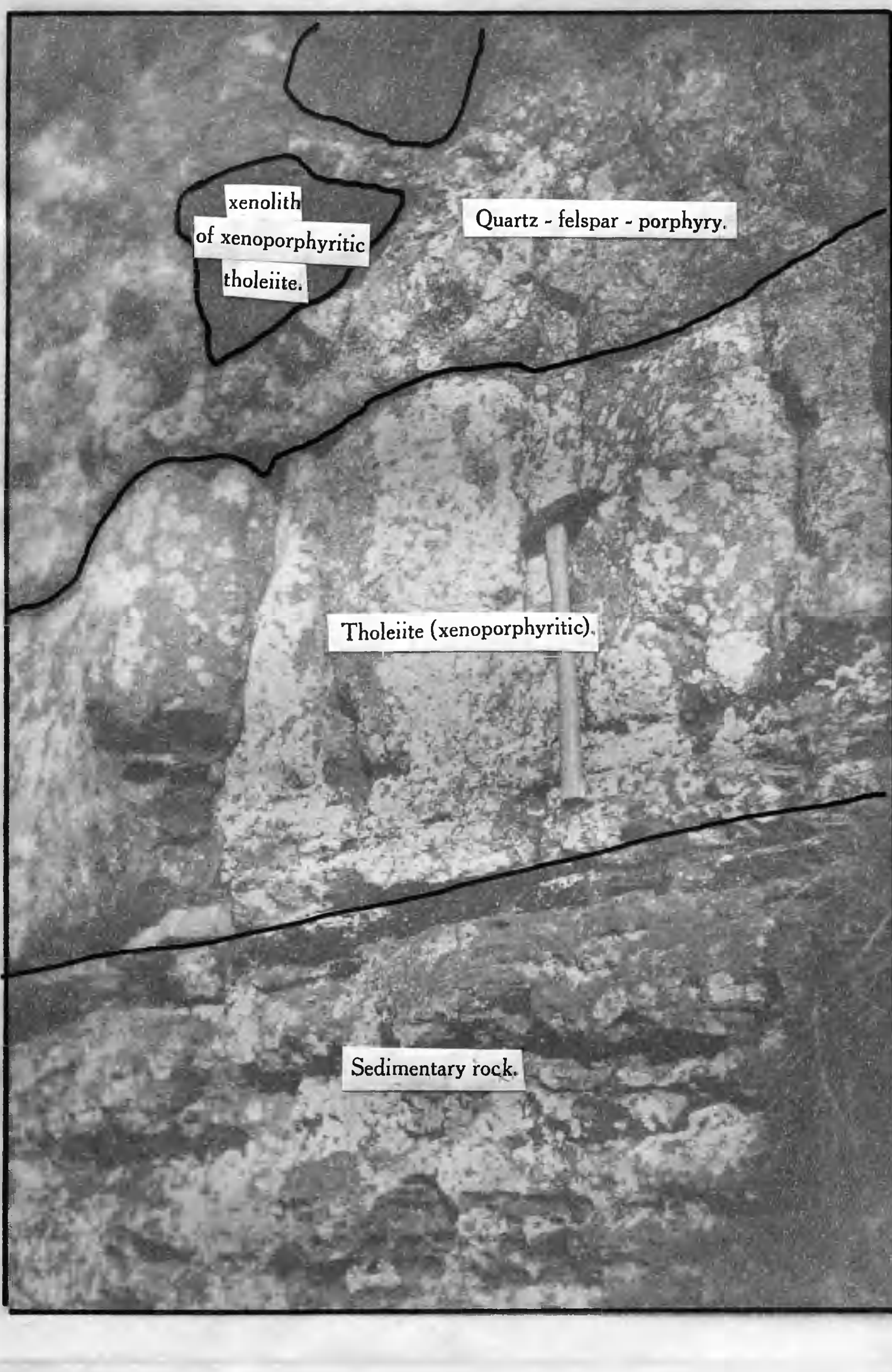
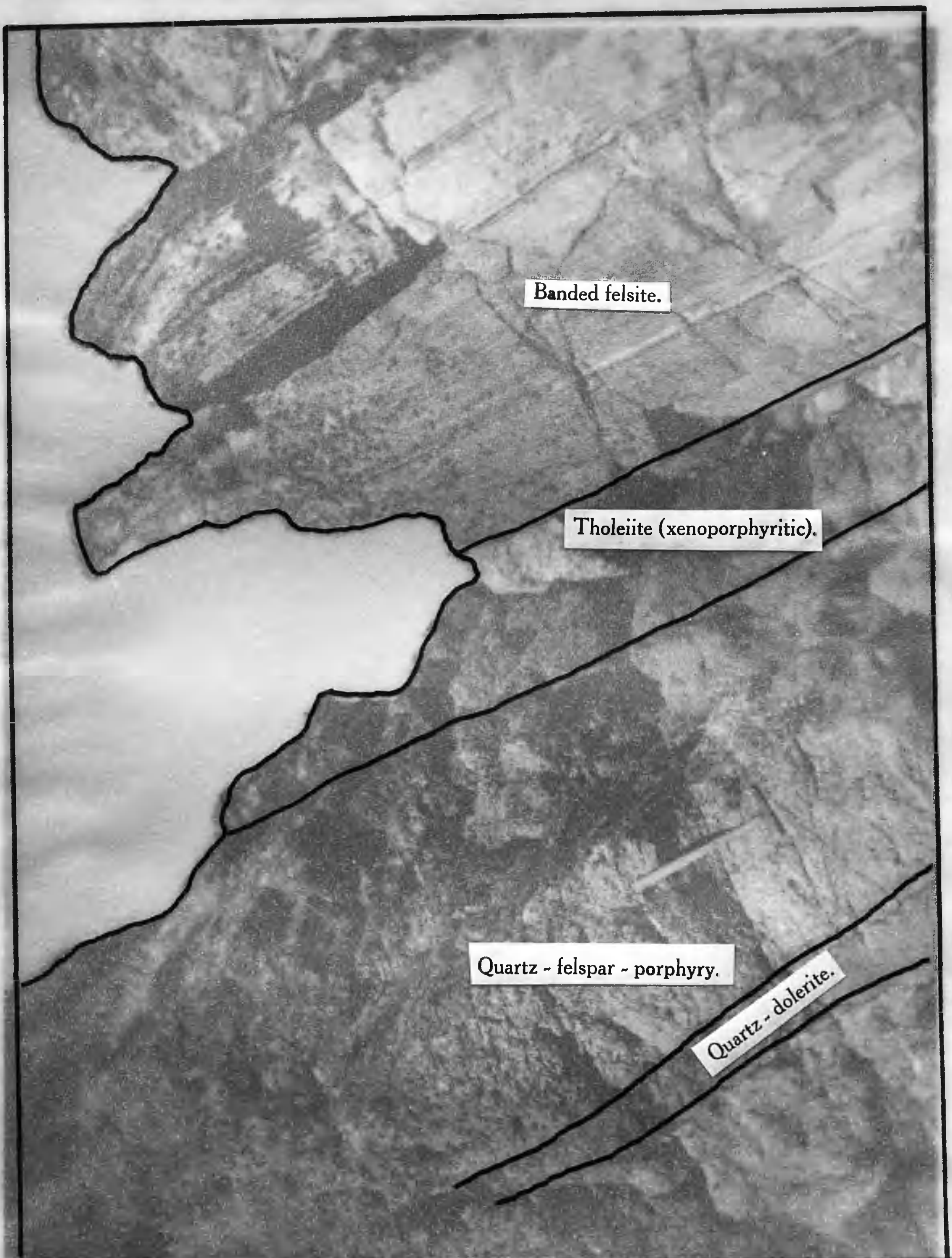

xenolith
of xenoporphyritic
tholeiite.
Quartz - felspar - porphyry.
Tholeiite (xenoporphyritic).
Sedimentary rock.

PLATE II

PLATE III



Banded felsite.
Tholeiite (xenoporphyritic).
Quartz - felspar - porphyry.
Quartz - dolerite.

PLATE III

PLATE IV

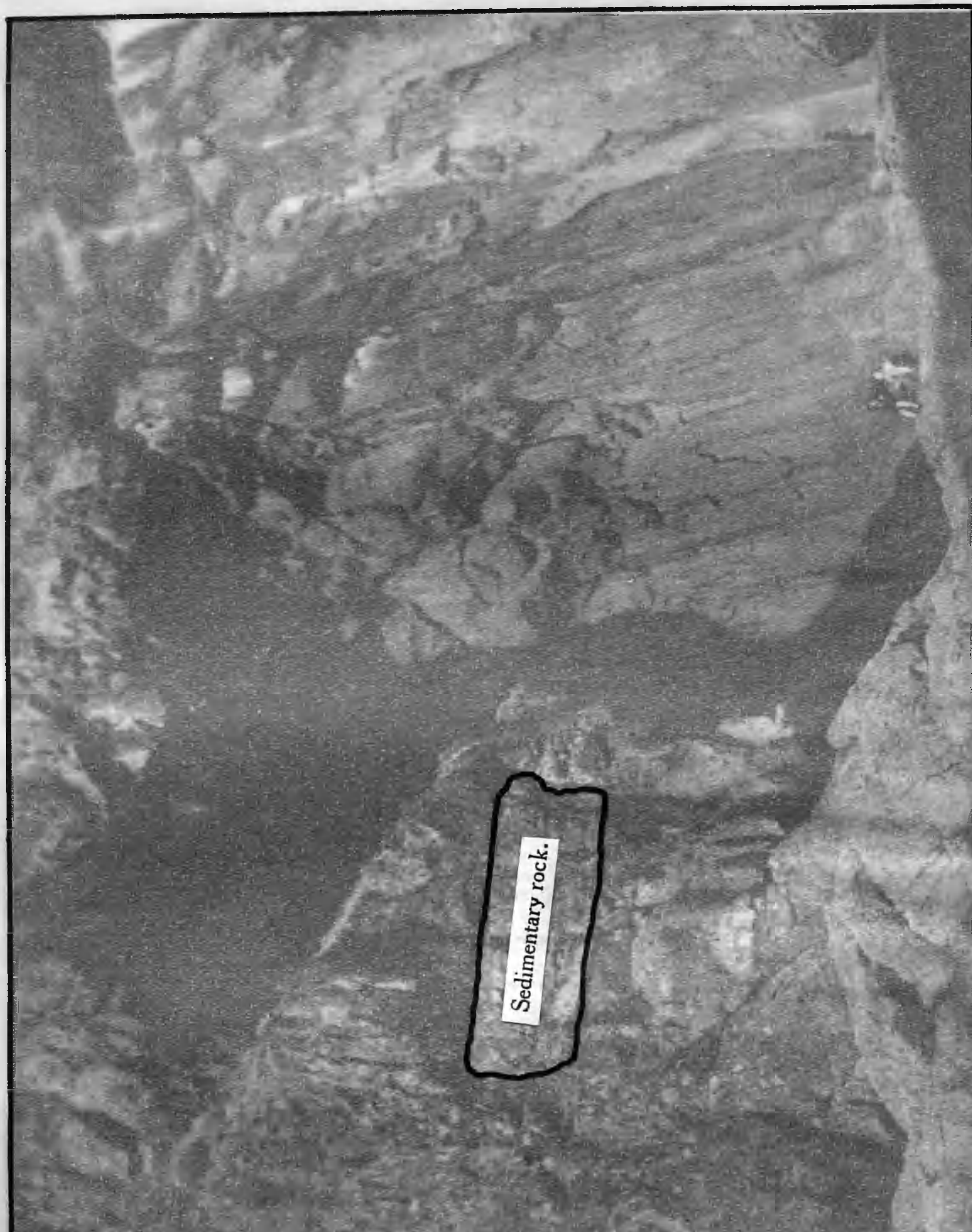


PLATE IV

PLATE V

PLATE VI

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2

3

4

PLATE VII

1

2

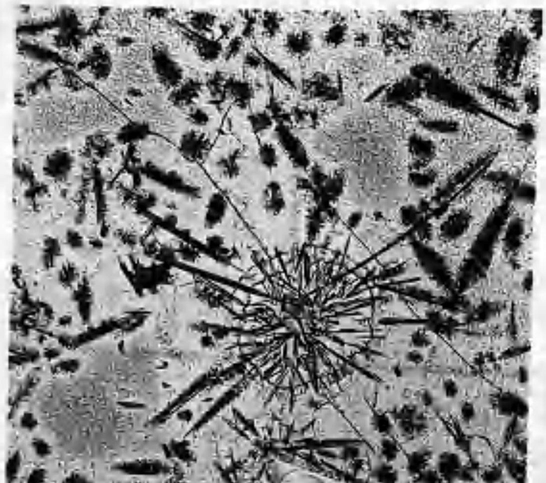

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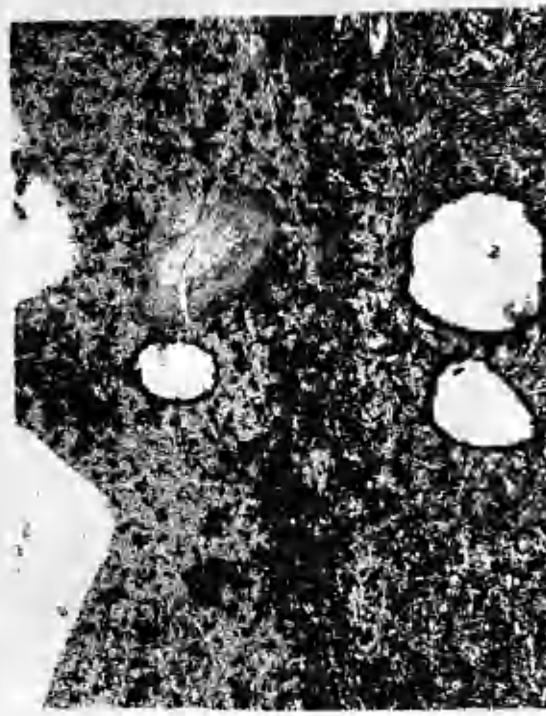
PLATE VIII

1



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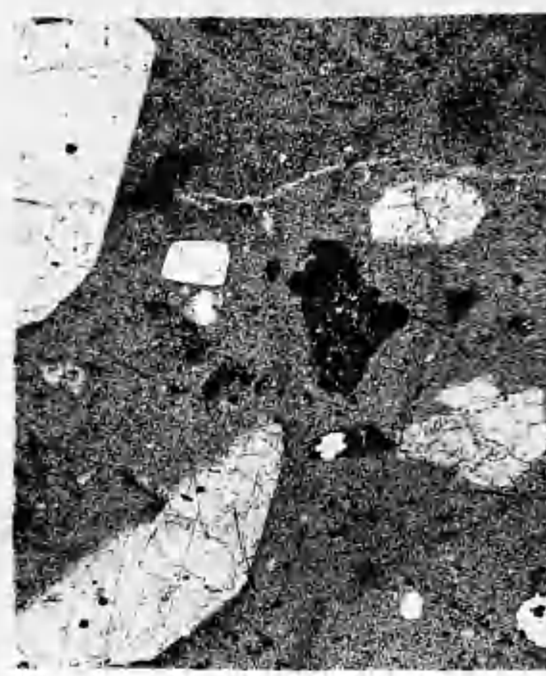

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PLATE IX

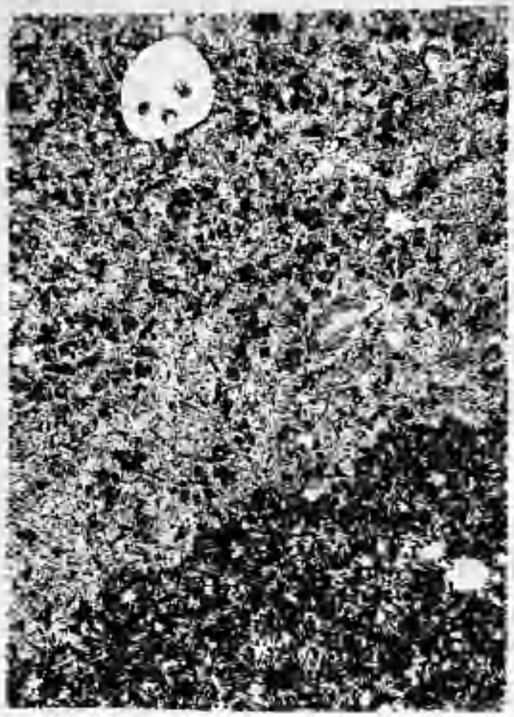

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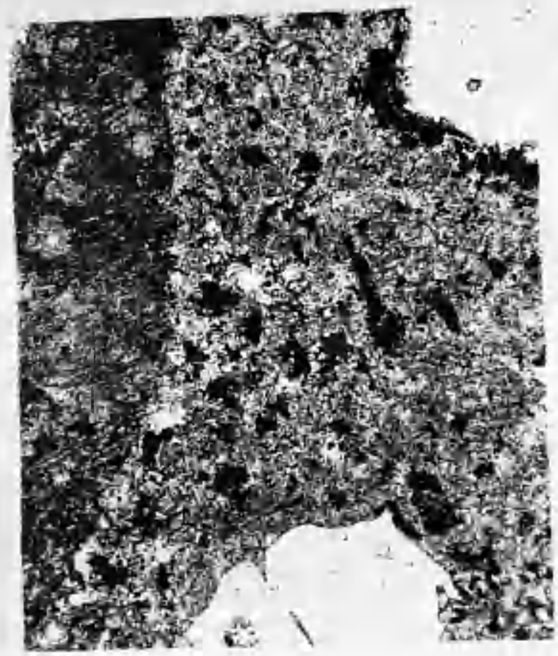
PLATE X

1



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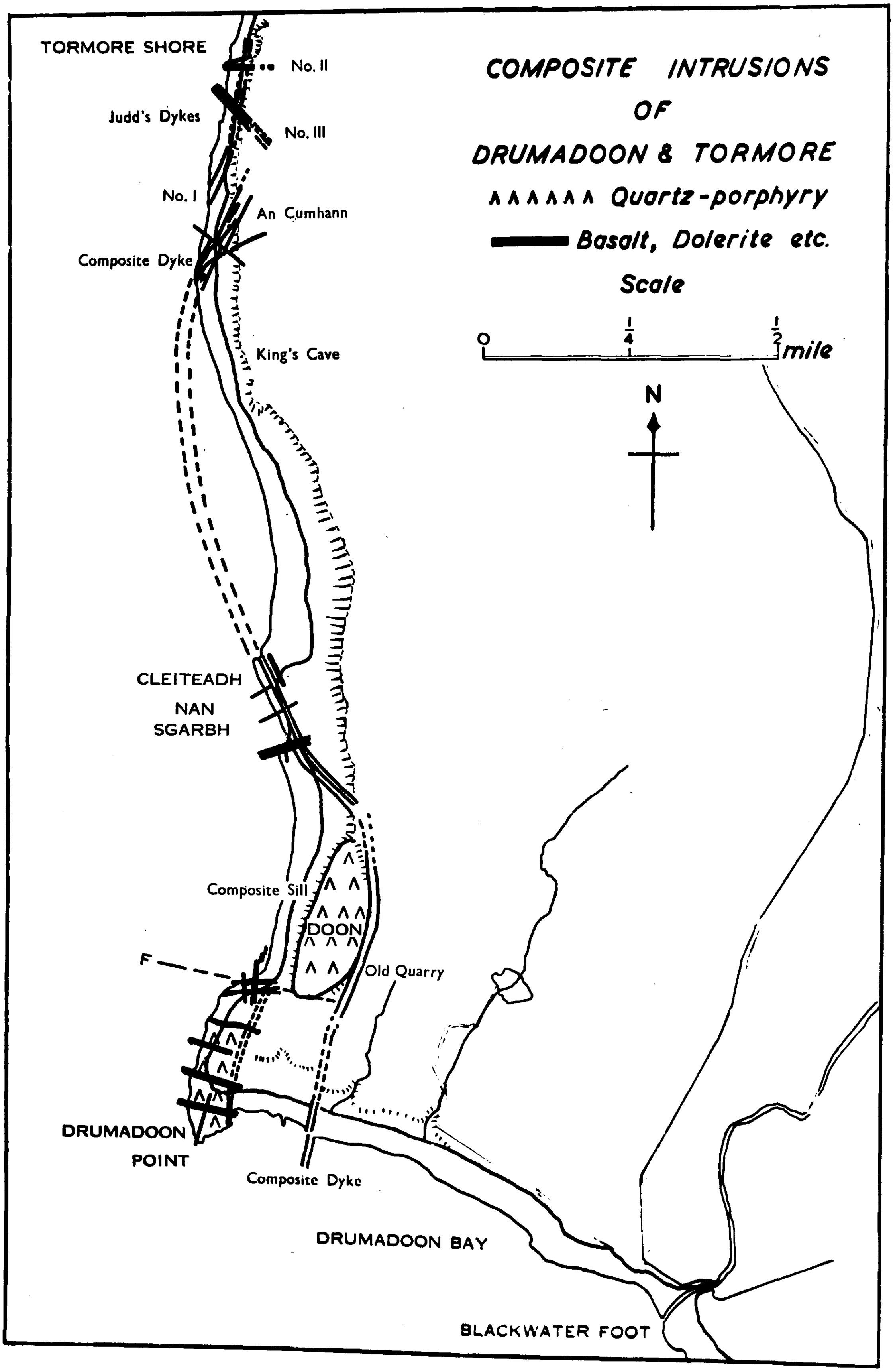
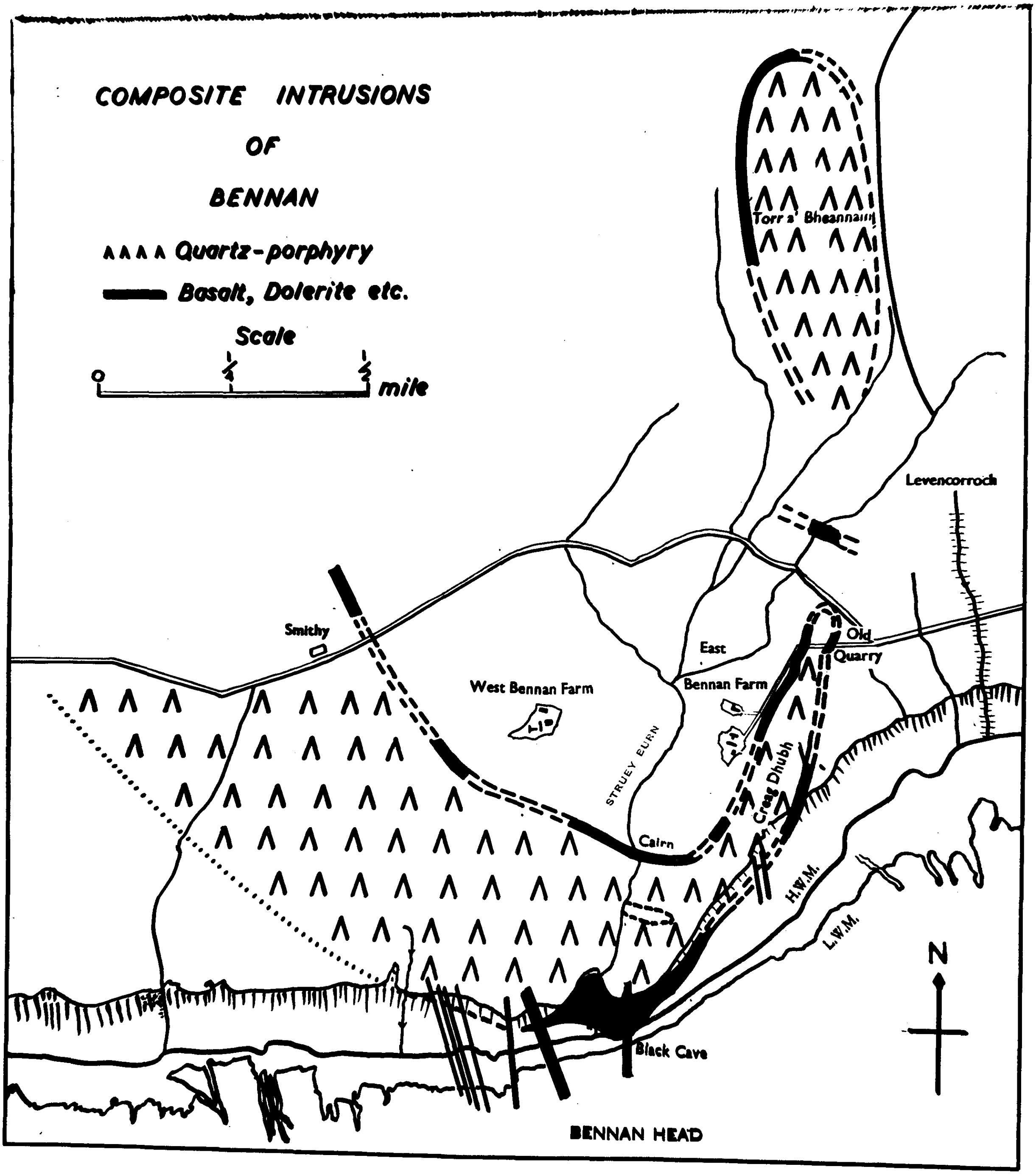

COMPOSITE INTRUSIONS
OF
DRUMADOON & TORMORE
ΛΛΛΛΛΛ Quartz-porphyry
Basalt, Dolerite etc.
Scale
0
1/4
1/2 mile
N
TORMORE SHORE
No. II
Judd's Dykes
No. III
No. I
An Cumhann
Composite Dyke
King's Cave
CLEITEADH
NAN
SGARBH
Composite Sill
DOON
Old Quarry
F
DRUMADOON
POINT
Composite Dyke
DRUMADOON BAY
BLACKWATER FOOT

Plate XII



COMPOSITE INTRUSIONS
OF
BENNAN
Quartz-porphyry
Basalt, Dolerite etc.
Scale
0
¼
½
mile
Torr a' Bheannain
Levencorroch
Smithy
Old
Quarry
East
Bennan Farm
West Bennan Farm
STRUEY BURN
Creag Dhubh
Cairn
H.W.M.
L.W.M.
N
Black Cave
BENNAN HEAD

No. XII.—Camptonitic Dyke Rocks from Inishowen, County Donegal, Ireland.

By M. V. N. Murthy, B.Sc., A.I.I.Sc., F.G.S. (In abstract).

(Read 10th April, 1947. Abstract published 1948).

This paper is a petrographic account[1] of a collection of camptonitic dyke-rocks from Inishowen, County Donegal, made by Dr. W. J. McCallien. His field notes show that these thin dykes are mostly concentrated in Malin Head and Inishtrahull Island round about Lag, Carrickvady and Dough; in the south, in Inch Isles and Buncrana; and in the west in Fanad. For a brief note on the geology of the region see preceding paper (No. XI). The rocks studied fall into five groups:—

1. Camptonitic rocks including the typical camptonites. These embrace types with panidiomorphic texture, the essential minerals being titanaugite, strongly pleochroic brown barkevikitic hornblende, and acid or basic andesine. Variations are seen first in the texture, viz., by the subhedrism of the mafic minerals which become ophitic or subophitic towards felspar, giving rise to dolerites, and secondly, in the composition, viz., in the relative proportion of titanaugite and brown barkevikitic hornblende. The rocks are microporphyritic, with pseudomorphs of olivine occurring both as euhedral phenocrysts and as irregular xenocrysts. Parallel growth between the augite and the hornblende, described by Flett from dyke rocks in the Orkney Islands (see "The Trap Dykes of the Orkneys," *Trans. Roy. Soc. Edin.*, 1900, vol. xxxix, p. 865), is found in the Inishowen rocks also. The ocelli, typical of camptonites, are mostly composed of fibrous spherulitic chlorite, calcite, felspar, or, in some cases, of analcite. They are surrounded often tangentially by biotite and felspar, the latter showing replacement by chlorite.

2. Camptonitic olivine-dolerite, a more coarse-grained type, with ophitic or subophitic texture and with a more basic felspar (basic andesine to acid labradorite).

3. Abnormal camptonitic rocks with phenocrysts of basic andesine or acid labradorite—a rather unusual feature in camptonites.

[1] See footnote to Paper XI, p. oo.

4. Monchiquitic rocks, characterised by olivine phenocrysts in a groundmass mostly of titanaugite, the base of the rock being probably analcite. A thin section of one specimen shows very interesting xenocrysts of olivine, titanaugite, anorthoclase, and magnetite, as well as xenoliths of augite-hornblende rock, plenonaste-peridotite, and sandstone, resembling similar occurrences described from the Oban and Dalmally districts and the Northern Highlands of Scotland. Sections intermediate between monchiquite and camptonite are also described.

5. Bostonitic rocks: a few of the slides available show types with bostonitic affinities, characterised by the predominance of felspar laths, often in trachytoid arrangement. These are described, together with some that appear to be intermediate between camptonitic and bostonitic rocks.

The study of these Inishowen dykes suggests that in all probability they belong to the same suite, and that the various distinct rock-types have been brought about by magmatic differentiation under varying conditions. The bostonitic types are believed to be complementary to the other rocks. Comparison with similar rocks in Scotland shows that the Donegal suite has the same peculiarities and leads to the conclusion that the Donegal rocks belong to the same period of dyke-formation, i.e. Permian. The descriptions extend the province of the Permian dykes to Northern Ireland, thus adding one more relationship between the geology of that province and the geology of Scotland.

The present investigation has been carried out under the supervision of Dr. G. W. Tyrrell.

SOME DYKE ROCKS FROM INISHOWEN

CO. DONEGAL, IRELAND.

C O N T E N T S

INTRODUCTION AND PREVIOUS LITERATURE.

The following account is the result of a study of the petrography of certain dyke rocks mainly from Inishowen, Co. Donegal, N.W. Ireland. The specimens were collected by Dr. McCallien, formerly of the Department of Geology, Glasgow University. Unfortunately, many of the hand-specimens were lost, but the thin sections were preserved. At the suggestion of Dr. Tyrrell and under his guidance, the author undertook the study of the microsections along with the few remaining hand-specimens. This paper is mainly a petrographic account of those slides, supplemented by such petrological considerations as could be deduced from that study and from the scanty geological data preserved on the labels of slides and specimens.

There is little literature on these dyke rocks except the scanty petrographical notes by Hyland,(7) published in the Memoirs of the Geological Survey of Ireland for Inishowen (1890), and N.W. and Central Donegal. (1891). In the former, Hyland describes a few camptonites from Dunree Head. From his description of/

of the dolerites from Keelagan Bridge, Dunaff Head etc. seem to resemble the camptonitic olivine-dolerite, described in the present paper. In the second memoir, what is described as plagioclase-hornblende-augite-olivine rock may represent the camptonites, though it is very difficult to come to definite conclusions from the descriptions. The only other reference is probably by Berger. (1)

GEOLOGY OF THE AREA.

Co. Donegal is mainly composed of metamorphic rocks, crystalline schists, gneisses, quartzites, crystalline limestones and dolomites of Dalradian age. These are an extension of the metamorphic series of S.W. and Central Scotland. They are intruded by igneous rocks of various ages. First the epidiorite, then spilites and keratophyrea, and later lamprophyres and porphyrites of Caledonian age. Camptonites and monchiquites were later intruded and lastly crinanites, basalts and tholeiites. The western part of the county especially is occupied by granite which is later than the epidiorites and earlier than the dykes.

Dykes of Caledonian age (marked as felstone and felstone porphyry in the one-inch map) have a general N.E. - S.W. trend, while the Tertiary basaltic dykes are mostly N.W. - S.E. The directions of the camptonitic rocks are not certain, since they are not described in the memoirs or noted in the one-inch maps. The dykes have been affected by faults of the area.

Dr. McCallien's field notes on these dykes are scanty, but we get the following information:-

(1)/

(1) The Caledonian dykes, i.e. the lamprophyres porphyrites etc., are distributed mostly in the western half of Inishowen round about Lag, Dough, Ballyfin, Dunree Head, Stragill, King and Queen of Mintiaghs, Rathmullan and Tyrone.

(2) The camptonitic rocks are mostly concentrated in Malin Head and Inishstrahull Island, round about Lag, Carrickvady, Dough, and in the south in Inch Isles and Buncrana, and in the west in Fanad.

(3) The distribution of the tholeiites and crinanites is not well defined, though they appear to be concentrated in the eastern half of Inishowen.

(4) The camptonites, tholeiites and bostonitic dykes appear to be comparatively thin, being about two feet in width. The dolerites range from five to ten feet in width.

(5) The lamprophyres and porphyrites occur both as sills and dykes whereas camptonites, crinanites and tholeiites are described only as dykes.

PETROGRAPHY.

The/

The rock sections studied fall into the following petrographical groups and are described under the following headings:-

(1) Camptonitic rocks including the typical camptonites.

(2) Camptonitic olivine-dolerites.

(3) Abnormal camptonitic rocks with felspar phenocrysts.

(4) Monchiquitic rocks including intermediate varieties between camptonites and monchiquites.

(5) Bostonitic rocks with an intermediate type between bostonite and camptonite.

(1) Camptonitic Rocks.

The majority of rock-sections studied belong to this group. Under this heading are included various dyke rocks with panidiomorphic texture (due to the idiomorphism of the mafic minerals), the essential minerals being titanaugite, brown barkevicitic hornblende, and plagioclase felspar. Variation is seen in (1) texture by the subhedrisim of the mafics, which become ophitic or subophitic towards the felspar, giving rise to dolerites (2) and in composition, i.e. mutual proportions/

proportions of titanaugite and brown barkevicitic hornblende. In most cases, the augite is in excess of the hornblende and sometimes is equal in amount to it, the reverse being very rare.

Rosenbusch (16) and Ogilvie (10) restrict the term camptonite to hornblende-plagioclase rocks. But it is felt by the author that the term could be used to include this series of rocks which though quite naturally show variations, still belong to a genetic series. The term will emphasise their derivation from a common stock. Rocks from Scotland have been described by various authors as camptonites irrespective of similar variations in the amounts of brown barkevicitic hornblende and titanaugite.

In the hand-specimens, the rocks are dark grey and fine-grained. Examination with a lens reveals shining laths of felspar and lustrous oval patches (sometimes rounded) of a white mineral which proves to be calcite on testing with acid. The rest of the rock is composed of irresolvable dull looking patches of altered minerals. The ocelli are very small, being less than 0.5 cm. in diameter.

On microscopic examination, most of the rocks appear/

appear to be microporphyritic, with phenocrysts of olivine. Porphyritic augite is very rare. The groundmass is composed of the essential minerals, titanaugite, barkevicitic hornblende, plagioclase felspar and the accessories, biotite, magnetite, titanomagnetite, pyrites and apatite. There are a few sections which may be termed typical camptonites because of the euhedrism of the mafic minerals, anhedrism of the plagioclase (basic andesine to acid labradorite) and the ocelli filled with analcite bordered by biotite flakes. In these sections, barkevicitic hornblende and titanaugite occur in equal proportions, but in a large number of sections variations are seen.

Description of Minerals.

Olivine occurs both as euhedral microphenocrysts and also as irregular or corroded grains, probably due to reaction with the magma. They are surrounded in many cases by euhedral, primary magnetite. The crystals show a tendency to grow attached to one another along the crystallographic axis 'c'.

Olivine is present only as pseudomorphs mostly/

mostly, replaced partially or completely by carbonates. It also alters to colourless or greenish serpentine dusted with magnetite or hematite. Often a part or a whole of the mineral alters to fibrous bowlingite, the colour and pleochronism varying in different rock sections from yellow to green, greenish yellow to pale green with the maximum colour along the fibres. It shows high birefringence and straight extinction. Another product of alteration of olivine is colourless non-pleochroic talc with low refringence and high birefringence. According to Winchell,(24) talc is an unusual alteration product of olivine in igneous rocks. Irregular grains of secondary silica are often seen in the pseudomorphs. A few sections show comparatively large xenocrysts of olivine, represented by pseudomorphs of calcite, bowlingite and secondary silica. They are surrounded by a zone of reaction composed of magnetite and granular calcite.

Titanaugite. Colour of the crystals varies from very pale to dark lilac-brown. It is rarely porphyritic but in many cases occurs in two generations in the groundmass. Cross-twinned crystals are found in many cases/

cases giving rise to radiating groups. The first generation of crystals are mostly euhedral, those of the second generation tending to appear subhedral and show a smaller intensity of colour than the former. They occur mostly as prismatic crystals, some as eight-sided sections. Cleavages are not seen distinctly but transverse irregular cracks are characteristic. They are non-pleochroic or indistinctly pleochroic. Maximum extinction angle recorded is 44°. The crystals show high birefringence and distinct dispersion and hence do not show complete extinction under crossed-nicols. 2 V could not be determined with the Federov stage since the crystals are either too small or too altered for determination.

An interesting feature is the occurrence in most sections of parallel growth between titanaugite and barkevicitic hornblende but rarely intergrowth between them. Sometimes barkevicitic hornblende encloses titanaugite or occurs on either or both ends of the latter. Invariably the hornblende is euhedral. This feature is confined mostly to the first generation crystals. Alteration. Titanaugite occurs mostly altered/

altered or partly altered, seen as greenish pseudomorphs. The presence of titanaugite most often has to be inferred, since no remains of any unaltered mineral are seen. They are identified by their shape and characteristic alteration products. The pseudomorphs are pale green chlorite, slightly pleochroic, with very low refringence and birefringence, sometimes almost isotropic. Some are distinctly pleochroic, from yellow to green, with straight extinction and unusually high birefringence. All of them contain numerous minute dark bodies which appear to be crystalline and translucent under high power. By reflected light, they are greyish-white and resemble leucoxene. They are irregularly distributed, but sometimes show a tendency to occur concentrated in transverse lines, probably the cracks of the original titanaugite. The shapes of the pseudomorphs are mostly prismatic. Partially altered crystals occur in a number of sections, showing the processes of alteration. The author agrees with Flett (3) in his belief that most of the pseudomorphs occurring in camptonites which were thought to be altered hornblende, are actually due to alteration of titanaugite. In sections where parallel growth/

growth is seen between titanaugite and barkevicitic hornblende, it is usual to find the latter to be attached to a chloritic pseudomorph. This has been mistakenly thought to be due to alteration of hornblende, but the boundary between the two is always sharp and straight. In the same section, it is usual to find unaltered brown hornblende, unattached to any mineral or pseudomorph. The dark crystalline bodies are due to the release of titanium during the alteration and probably represent ilmenite ($FeTiO_3$) altered to leucoxene.

In two slides (D.442 and D.438) the 2 V as determined with the Federov Stage varied from 51^o to 55^o about Z. This angle is higher than the one recorded for titanaugites in other rocks. The augite is almost colourless and probably more diopsidic. It is significant that these rocks come from areas other than Malin Head (Glenalla and Rathmullan).

Barkevicitic Hornblende occurs only in one generation, almost always in the groundmass, euhedral to subhedral, in reddish prismatic crystals. It is mostly fresh and has probably greater resistance to change than titanaugite. It alters sometimes to chlorite and leucoxene, showing its/

its titaniferous nature. It is pleochroic; yellow = x, yellowish brown = y, dark brown = z. $z > y > x$. It has high refringence and birefringence, but interference colours are masked due to absorption. It has a low extinction angle, the maximum measured being 18°. As previously described, it shows parallel growth with titanaugite and in most cases is of later crystallisation than the latter. 2 V measured on the Federov Stage is 76° - 80.5° about x.

Felspar. In the sections studied, only plagioclase felspar occurs in anhedral prismatic crystals moulded on minerals of earlier crystallisation. They occur both in the groundmass and the ocelli. They are mostly unaltered and in a few cases show sericitization. They occur both as twinned (twinning according to albite law and also Manebach law) and also as untwinned prisms or plates. They have extinction angles from 15° to 30° and hence correspond to acid to basic andesine. They show inclusions of titanomagnetite and apatite crystals. They are not zones and frequently show undulose extinction.

Accessory Minerals.

Biotite is found in almost all sections occurring in small/

small flakes or hexagonal basal sections, reddish brown in colour, showing the characteristic dark brown absorption. Sometimes it is difficult to distinguish it from barkevicitic hornblende. In most cases they are attached to magnetite crystals.

Magnetite is an important accessory occurring as euhedral, subhedral and also anhedral crystals. Some of these crystals appear whitish-grey in reflected light, due to their titaniferous nature. Besides, there are a large number of irregular bars of magnetite. In many cases they occur as skeletal growths of various shapes and sometimes they appear whitish grey in reflected light. These represent titanomagnetite.

Pyrites is a very minor though widespread accessory varying from dust-like grains to comparatively big patches. The red hematite seen in some sections is probably due to alteration of pyrites.

Apatite is an important accessory, occurring in needle-like crystals of various sizes. They appear especially in the felspars. The ocelli are comparatively rich in apatite.

Ocelli cavities etc.

Ocelli in the original sense of Rosenbusch (5) as areas of analcite, bordered tangentially by biotite etc., occur only in a few cases. In most rocks they are felspathic and/or chloritic. Probably they may be better called cavities. Besides these there are numerous lacunae with chloritic mineral felspathic interspaces.

Most cavities are filled with a fibrous mineral, in spherulitic growths. It is difficult to assign it to a particular species. All fibres show straight extinction and positive elongation, the difference in the varieties being in colour, pleochroism and birefringence. (a) Pale green fibres; the colour is more intense in the spherulite, very slight pleochroism, interference colours are red of the first order. (b) pale yellowish green, slightly pleochroic, very pale yellow = X, yellowish green = Z. First order red polarisation colours. Some fibres with similar characters show low interference colours (first order grey). (c) Almost colourless fibres, some show first order grey and some first order red polarization colours. Probably all of them belong to the chloritic group, the differences seen being due to difference in content of iron. Besides, the fibrous mineral, calcite occurs in irregular grains or crystals occupying mostly the/

the interior of the cavities. In many felspathic cavities there are numerous idiomorphic crystals of hornblende, biotite, apatite titanomagnetite and plagioclase felspar. The felspar occurs in both prismatic crystals and feathery or dendritic growths. The crystals of the ocelli appear to crystallize in comparatively larger sizes. They are lined with biotite flakes in many cases. In a few instances, the ocelli are filled with clear analcite, the periphery sometimes showing slight anisotropism. None of the slides examined show olivine or titanaugite in the ocelli.

(z) Camptonitic Olivine-Dolerites.

A few sections showed comparatively more coarse grained and ophitic or subophitic texture due to plagioclase laths penetrating titanaugites. They are olivine bearing, the mineral occurring always as phenocrysts. Titanaugite predominates over barkevicitic hornblende, the latter being very small in quantity. Both the minerals are subhedral. Similar rocks elsewhere have been called olivine dolerites but the author feels that the term camptonitic olivine dolerite will give them a more genetic significance/

significance, emphasising their genetic relationship with the camptonitic rocks. The camptonitic affinities are clearly indicated by the presence of titaniferous augite and hornblende, and the occurrence of ocelli and lacunae.

In the handspecimen, the rock is comparatively more coarse grained than the camptonitic rocks, laths of felspar and ocelli with calcite are recognisable. Microscopically, most of the characters are the same as in the camptonites. Besides olivine phenocrysts, a few xenocrysts occur as described under camptonites. Titanaugite appears to be fresh or partially altered in most specimens. Parallel growth between titanaugite and barkevicitic hornblende is comparatively rare. Plagioclase felspar in anhedral prisms or laths is more basic, ranging from basic andesine to acid labradorite (extinction angle 19^{o} to 38^{o}) and bi-axially positive. Short, stout bars of titanomagnetite appear to be very characteristic. No ocelli with analcite were noted but cavities with felspar, chlorite, calcite etc. are very common. The lacunae occur as described previously. In one section (D.208) the hornblende, occurring in the chloritic/

chloritic cavities, shows a pale bluish colour, with pleochroism from yellow to bluish-green (extinction angle 22°), similar grains being absent in the groundmass of the rock.

ABNORMAL CAMPTONITIC ROCKS WITH FELSPAR PHENOCRYSTS:

In all camptonitic rocks the plagioclase is anhedral and subordinate, and it rarely assumes porphyritic dimensions. Some of the sections, especially from Inishtrahull Island, show two generations of plagioclase, the first occurring as phenocrysts, the second as prisms and laths in the groundmass. There is great variation in this tendency, the best section being D.25 where olivine, titanaugite and plagioclase occur as phenocrysts, making the rock an abnormal type. Only titanaugite and plagioclase exhibit a second generation of crystals. The felspar phenocrysts occur in large rectangular sections, mostly twinned on the Albite law, and also on Manebach law. They show a maximum extinction of 35°, corresponding to basic andesine or acid labradorite in composition. Titanaugite has a tendency to occur in glomeroporphyritic groups.

Monchiquitic/

(4) MONCHIQUITIC ROCKS.

Four of the rock sections showed distinct monchiquitic tendencies. They are characterised by olivine phenocrysts in a groundmass of mostly titanaugite, the base of the rock being a mineral of low refractive index and almost isotropic. It is probably analcitic.

They are microporphyritic, largely idiomorphic with phenocrysts of olivine of comparatively large size. In two sections the olivines occur as fresh or partially altered crystals. They have high refringence and very high birefringence . Though most sections show straight extinction, it is interesting to note that some exhibit inclined extinctions, the maximum angle measured being 20°. This is probably due to the fact that these sections are parallel to the pyramidal face, as explained by Johannsen (9). 2 V, measured with Fedorov Stage is very high (84° to 88°), the sections being optically positive or negative. In two sections olivine occurs in crystals of two generations.

Titanaugite occurs in two generations, the crystals being euhedral and of various sizes. They

form,

form porphyritic crystals or glomeroporphyritic groups. They are all fawn coloured, the colour being more pronounced in the edges. Some of them show a colourless interior of diopside and a coloured outer zone of titanaugite. Hour-glass structure is very characteristic. They are distinctly pleochroic: Yellow = X, Yellowish brown = Y, Lilac brown = Z, Z Y X. The titanaugite is very rarely altered.

Brown barkevicitic hornblende and biotite are almost absent except in the ocelli and where they occur, they show the usual characters. Titanomagnetite appears to be uncommon, but euhedral to anhedral grains of magnetite appear as an important accessory. Apatite does not occur in large quantities. A few anhedral plagioclase crystals are seen (basic oligoclase to acid andesine in composition). The base of the rock, as described previously, is very probably analcitic, the slight anistropism being due to alteration.

Rock D.82 (boulder opposite sill in small island, Carrickavady, Inishowen, Co. Donegal) is very interesting and hence deserves special description. It/

It is a monchiquite, showing very interesting xenocrysts of olivine, titanaugite, anorthoclase, magnetite and xenoliths of augite, hornblende rock, augite rock, pleonase peridotite and sandstone. In handspecimen, the rock is dark grey and compact, except for a number of oval patches of minerals some measuring a cm. across. One of them is composed of a black shining material. There is another patch composed of bronze yellow grains. There are a number of shining oval patches which are probably augite. One interesting patch shows a shining yellowish brown translucent mineral, with numerous transverse cracks.

Microscopic examination shows that it is composed of all the minerals of a monchiquite. Olivine occurs as small euhedral crystals and larger patches with rounded edges. Crystals of titanaugite appear attached throughout to the exterior of the olivines, their formation probably to be attributed to reaction between olivine and the magma. In a few cases the augite crystal appears to penetrate the olivine crystal. The euhedral olivine phenocrysts are obviously different from the second type which are xenocrysts. This view is/

is supported by the presence of spinel as an inclusion in an olivine pseudomorph, indicating its source in the pleonaste peridotite, xenoliths of which occur in the same section.

Titanaugite also occurs in euhedral phenocrysts, and as large patches of anhedral xenocrysts. All of them show evidence of magmatic reaction. They show (1) zoning; (2) hour-glass structures, (3) in some crystals the interior is sown with a number of small particles of iron ore, (4) little granules of colourless diopside surrounded by a rim of titanaugite, (5) intense magmatic reaction is seen in the anhedral xenocrysts, which show a colourless granular core, surrounded by a zone of reaction of dark irresolvable bodies with an outer rim of lilac-brown titanaugite.

In addition to these, there are large patches representing augite nodules, all lying in different orientations, but enclosed in a rim of titanaugite, with a reaction zone in between them. The augite grains show regular inclusions of dark bodies, oval in shape, arranged parallel to the cleavages. Besides these there are a few serpentinised and carbonated inclusions of probably olivine.

One/

One of the sections of this rock shows an interesting xenolith composed of anhedral, colourless augite and brown basaltic hornblende (pleochroism from yellow to brown), with maximum extinction angle of 25°. Both minerals are surrounded by a rim of titanaugite.

Two sections of the rock show xenoliths of pleonaste periodotite composed of anhedral serpentised and carbonated olivine and fresh or uralitised diopside. The spinel is yellowish brown pleonaste, sometimes with a rim of magnetite.

Xenoliths of quartzose material are found in two sections of the rock, probably representing country rock. They are composed of irregular quartz grains, closely packed with an irresolvable dark cementing material. There are irregular patches of pyrites. There is a zone of reaction composed of large numbers of radiating long prismatic crystals of diopside, very different from the lilac brown titanaugite of the groundmass.

D.82c shows a very interesting patch of a colourless mineral with a low extinction angle and patchy extinction; this is anorthoclase. There is no zone of reaction between this and the rock. One of the sections shows/

shows an oval patch of magnetite.

The interest of this rock is obviously in the large variety of xenocrysts and xenoliths it contains.

An interesting feature is noticed in D.187. A number of phenocrysts of altered olivine enclose crystals of lilac brown titanaugite, with distinct pleochroism from yellow to lilac brown, definitely showing that titanaugite is earlier in crystallization than olivine, which is a rather unusual phenomenon. The olivine encloses magnetite also.

Two sections appear to be intermediate between monchiquites and camptonites. D.73 is megascopically a very fine-grained compact rock. Microscopic examination reveals a number of comparatively large olivine phenocrysts occurring only as pseudomorphs of calcite and secondary silica. The groundmass is composed of very small prisms of titanaugite and barkevicitic hornblende, in equal proportions. The augite crystals are the larger. The base of the rock is almost isotropic, but for the very small laths of plagioclase with almost straight extinction (basic oligoclase). Magnetite is

an/

an important accessory. There are a number of ocelli with brown barkevicitic hornblende prisms and felspar laths. There is a long, irregular, vein-like patch, in which are found flow-oriented and also feathery felspar, besides small irregular grains of carbonate. D.210 is also a similar rock; the numerous ocelli in this section are filled with analcite. There is an interesting patch in this section with a pale green isotropic glassy base, in which are set the minerals of the rock. Mineralogically, these two sections are camptonitic, but show definite monchquitic affinities by the presence of an isotropic base, probably of analcite.

(5) BOSTONITIC ROCKS.

About six slides with bostonitic affinites were examined. They are characterised by the predominance of felspar laths, often in trachytoid form. A few show phenocrysts of plagioclase (basic oligoclase to acid andesine), round which the prismatic laths of basic oligoclase are flow-oriented. D.146 shows dendritic growths of plagioclase. All the felspar, both laths and phenocrysts, show sericitization. A few clear, irregular,/

irregular, colourless, untwinned grains with low refringence and low birefringence, optically positive, occur, distributed among the felspar laths and probably are secondary albite grains.

Besides the felspars, they contain in varying amounts, a subordinate quantity of chlorite-leucoxene pseudomorphs, similar to those seen in camptonitic rocks, which probably represent original titanaugite. Primary magnetite is absent, though small patches of limonite occur. Small flakes of biotite and sometimes big crystals of apatite occur in the slides.

There are two interesting sections, one from Inch Isle, representing a bostonitic rock with spherulitic structure. In this section there are a number of needle-like chloritic pseudomorphs also. D.304 appears to have both bostonitic and camptonitic affinities (Maenaite?). It is composed of olivine phenocrysts, serpentinised and carbonated and also phenocrysts of basic oligoclase in a groundmass of oligoclase laths and chloritic-leucoxene patches representing probably titanaugite. An indistinct trachytoid texture can be seen in some places around phenocrysts. Apatite needles/

needles and euhedral magnetite grains occur as accessories, besides small skeletal rods of titanomagnetite, occurring in groups. There are a number of cavities filled with fibrous chlorite and carbonate. Camptonitic affinities are indicated by the presence of olivine, titanaugite, titanomagnetite and cavities with infillings. Bostonitic characters are revealed by the richness in plagioclase of an acid composition occurring both as laths and phenocrysts and the occasional trachytoid texture. The rock appears to be intermediate between camptonites and bostonites.

PETROGENESIS.

In the absence of field evidence, it is obvious that conclusions arrived at in this paper are essentially based on microscopic study. The rocks described are all dyke rocks with distinct alkaline affinities as indicated by titanaugite, barkevicitic hornblende and analcite. All of them show these common features (except the bostonitic rocks), the presence of (a) microphenocrysts of olivine, (b) titanaugite and barkevicitic hornblende, (c) ocelli or cavities, (d) titanomagnetite in all sections, (e) olivine xenocrysts in all the rocks. These characters emphasise the genetic unity of the series and it is felt by the author that these various types of rocks have been derived from the same common source, by a variation in composition brought about by crystallization-differentiation. Euhedral mafic minerals, especially titanaugite, brown barkevicitic hornblende and biotite, with anhedral plagioclase in subordinate amounts, give rise to the camptonitic rocks. Development of coarse grains, an increased felspathic content (more basic in composition than previously), with subordination of titanaugite and an ophitic or subophitic texture, gives rise/

rise to the camptonitic olivine dolerites. The tendency for increase in felspathic content and coarser grain size sometimes give rise to two generations of felspar, the first generation occurring as phenocrysts, leading to the formation of abnormal rocks in the camptonitic suite. By a decrease in the amount of felspar and almost complete disappearance in some cases, coupled with an increase in its acidity and an increase in the mafic minerals, especially olivine and titanaugite, with an isotropic analcitic base, monchiquitic rocks are derived. Regarding the bostonitic rocks it is not possible to say anything definitely since evidence is scanty, but the author feels that they may probably belong to this suite, occurring complementary to the camptonitic rocks. The presence of an intermediate variety between the camptonitic and bostonitic rocks supports this view.

The richness of the original magma in titanium is shown by the presence of titanaugite, barkevicitic hornblende (alteration results in leucoxene), reddish brown biotite and titanomagnetite. The last mineral is a very characteristic accessory. Its occurrence in skeletal growths even in the ocelli shows that the magma was rich in/

in titanium to the very last stages of crystallization, when the excess seems to have crystallised as titanomagnetite.

The absence of zonal structure in the felspars and also titanaugite in the camptonitic rocks shows that crystallization took place under fairly stable conditions. On the other hand, the monchiquitic rocks reveal mostly zonal and hour-glass structure and many other indications of magmatic reaction. The augite has a diopsidic core with a rim of titanaugite showing change in composition and conditions of crystallisation. According to Scott (17), hour-glass structure is most common in those rocks containing TiO_2. The magma must have been considerably rich in volatiles as shown by the presence of large numbers of apatite needles which are comparatively more abundant in the ocelli revealing thereby the increase in richness as crystallization proceeded.

It is found that most of the rocks are carbonatized, and the olivines are invariably replaced. Chloritization is confined to the cavities, and lacunae and to most of the titanaugites. The cavities are almost always filled centrally with calcite and surrounded by spherulitic chlorite fibres, which in many cases appear to have replaced calcite. A more interesting phenomenon is the replacement/

replacement of felspar laths around the cavities by fibrous chlorite, the original outline and part of the mineral preserved distinctly.(photomicrograph). These definitely prove that the changes noted above must be due to the last stages of magmatic activity, by the activity of the volatiles which accumulate as crystallization proceeds, rather than to weathering by atmospheric agents. Read (11) and Smith (18) hold similar views. It is probable that carbonatization took place first and later chloritization.

It has been recorded that biotite occurs in many cases around magnetite and is probably a product of reaction between it and the magma. Similar occurrence of biotite has been noted by Tyrell and Iwao.(8).

In many of the camptonitic rocks, occurrence of feathery felspar which appears to be oligoclase by its very low extinction angle, has been noted. Since these are the last to crystallize, they are probably enriched in soda, a fact substantiated by the occurrence of analcite in some of the ocelli.

In a number of the rock sections studied which include camptonitic rocks, camptonitic dolerites and a monchiquitic/

monchiquitic rock xenocrysts of olivine represented by pseudomorphs of calcite, bowlingite, serpentine and secondary silica occur. In the first two types, they are surrounded by a distinct zone of reaction, composed of granular carbonate mixed with grains of magnetite. The original mineral representing the product of reaction of the granular carbonate is not clear. In a similar case, Flett (4) has suggested that they may represent monticellite. In the monchiquitic rock the product of reaction is titanaugite which occurs as a rim of crystals round the xenocryst. The source of these olivine crystals must probably be attributed to the ultrabasic periodotite nodules found in the monchiquite.

COMPARISON WITH SCOTTISH OCCURRENCES.

Camptonitic and monchiquitic rocks have been described in Scotland from the Orkneys (3, 4) in the north to the Sanquhar (13) coalfield in the Southern Uplands in the south. They show a number of variations in composition and texture. The camptonites are more common in the Highlands, while the monchiquites are more common in the south, especially in the Midland Valley of/

of Scotland. Nevertheless, these have genetic affinities and have been considered to belong to the same epoch of dyke formation (Richey, 14), due to the same magmatic activity. Comparison of the Donegal rocks with the Scottish occurrences reveal remarkable similarities in rock types and mineral composition. The similarities are far greater than the minor variations and it may safely be postulated that they have genetic relationships and very probably belong to the same epoch.

Porphyritic camptonites with microphenocrysts of olivine, excess of titanaugite over barkevicitic hornblende have been described from the Orkneys (3), Coll (15), Ross of Mull (19), Central Ross-shire (4a) and many other places with slight variations. Macroporphyritic camptonites have been described from a large number of areas. Camptonitic olivine-dolerites are described from Mull (20), and Central Ross-shire (4a). Flett (3) describes abnormal camptonitic rocks with felspar phenocrysts from the Orkneys and Central Ross-shire. Monchiquitic rocks have been described in the north from the Orkneys (3), Coll (15), Central Sutherland/

Sutherland (12), Ross of Mull (19) and from Ayrshire (21) in the south. Thomas (19) notes from Iona dykes intermediate in composition and structure between the camptonites and monchiquites. Harker (5) refers to transition rocks from Ardmuckinisch. Bostonite dykes are noted by Flett (3, 4) who describes the occurrence of many from the Orkneys.

Mineralogically, they bear close resemblance to many of the Scottish rocks in the occurrence of olivine, titanaugite, barkevicitic hornblende and reddish biotite. Titanaugite has been described to occur in two generations and it shows hour-glass structure. Biotite is always noted as a subordinate mineral. Parallel growth between augite and hornblende has been invariably described. Ocelli as well as cavities similar to those described in this paper are reported to occur in all the Scottish rocks. Olivine and titanaugite never occur in the ocelli, a feature common to both areas.

Monchiquitic rocks show great resemblance in mineralogy and structure to Scottish rocks. More remarkable is the occurrence of xenocrysts of olivine, titanaugite and anorthoclase and xenoliths of augite rock/

rock, augite-hornblende rock, pleonaste-peridotite and sandstone, which have been noted from the Northern Highlands and Oban and Dalmelly. Boulton (2) and Tyrell (22) describe similar xenocrysts and xenoliths.

Minor differences between the Donegal dykes and the Scottish dykes have been noticed. (a) In grain size of the rocks, (b) occurrence of barkevicitic hornblende in excess of titanaugite in Scotland, (c) presence of alkali felspar in the Scottish areas, (d) zoned felspars are common in Scotland, (e) in most camptonitic rocks of Scotland, analcite has been described in the ocelli, but in the rock-sections studied, this mineral occurs only rarely.

AGE OF ROCKS.

There is no field evidence regarding the age of the dykes. The conclusion can be drawn only on the basis of their petrological similarities. In Scotland, camptonite and monchiquite dykes are considered Permian in age.(Richey 14). This view has been confirmed by radioactive determinations by Urry (23). It can only be said that they very probably belong to the Permian epoch of dyke formation.

SUMMARY AND CONCLUSIONS.

In this paper, the petrography of dyke rocks of camptonitic monchiquitic and bostonitic nature, mostly from Inishowen, Co. Donegal, N.W. Ireland, has been described. The author feels that all these rocks belong to the same suite, that the various distinct rock-types have been brought about by magmatic differentiation under varying conditions. The bostonitic rocks are felt to be complementary to the other rocks. Comparison with similar rocks in Scotland leads to the conclusion that the great similarities seen must be attributed to the origin of the Donegal rocks during the same epoch of dyke-formation, i.e. Permian. The description of these rocks from Donegal extend the province of the Permian dykes to Northern Ireland, thus adding one more relationship between the similarity in the geology of that area and Scotland.

The author wishes to express his grateful thanks to Dr. Tyrrell, for his guidance and constructive criticism of this study.

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DESCRIPTION OF PHOTOMICROGRAPHS.

(1) D.213a. Magnification 35. Ordinary Light.

Photograph shows an ocellus in a camptonitic rock, composed of prismatic felspars and dark minerals, which include brown hornblende, biotite, etc. The rest of the photograph shows the groundmass of the rock.

(2) D.65. Magnification 27. Ordinary Light.

An ocellus showing calcite in the centre, spherulitic fibrous chlorite surrounding it. The plagioclase prisms in the periphery show replacement by chlorite, the shape of the former is clearly seen. Some crystals are partially white, showing unreplaced felspar. The photograph shows how chlorite appears to replace calcite.

(3) D.212. Magnification 27. Ordinary Light.

Shows a xenocryst of olivine, now represented by a reaction rim composed of magnetite and calcite grains. Rock is a camptonitic olivine-dolerite.

(4) D.208. Magnification 35. Ordinary Light.

Camptonitic olivine dolerite showing subophitic relationship between titanaugite and laths of felspar.

(5) D.25. Magnification 35. Ordinary Light.

Abnormal/

Abnormal camptonitic rock showing idiomorphic phenocrysts of olivine seen as pseudomorphs and felspar phenocryst in the S.W. corner. The groundmass is composed of second generation augite, felspar and brown hornblende.

(6) D.82B. Magnification 35. Ordinary Light.

An olivine xenocryst, in a monchiquite represented by pseudomorph. Numerous dark crystals of titanaugite may be seen attached to it. To the right there is an augite crystal showing zonal structure. The groundmass is composed of mostly titanaugite and magnetite.

(7) D.82b. Magnification 20. Ordinary Light.

Photograph shows two xenoliths - (a) sandstone, upper left-hand corner and (b) pleonaste peridotite, in lower right-hand corner.

(8) D.325. Magnification 27. Crossed nicols.

Bostonitic rock, showing a phenocryst of felspar and flow-oriented minute felspar laths around it.

PHOTOMICROGRAPHS

(1)

(2)

(3)

(4)

(5)

(6)

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