THE IGNEOUS AND METAMORPHIC PETROLOGY
OF THE
GIRVAN-BALLANTRAE COMPLEX

by

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I. INTRODUCTION

The Girvan-Ballantrae igneous complex outcrops along the greater part of the coast from Girvan southwards to Ballantrae, a distance of some 12 miles, and extends inland for a distance of 4 miles at its widest part.

The complex is Arenig in age and occupies an area of approximately 45 square miles (Plate 1).

The southern margin of the complex trends NE-SW following approximately the line of the River Stinchar which occupies a broad valley and meets the sea at Ballantrae. A large reverse fault running parallel to the River Stinchar serves to define the southern margin of the complex which is sharply truncated against a series of younger greywackes, probably Caradocian in age, occupying higher moorland country to the south.

About 7½ miles to the NE of Ballantrae the Stinchar Valley, and the margin of the igneous complex, turns more to the north for a distance of 2 miles when the River Stinchar suddenly strikes off to the NE once more, leaving the boundary of the igneous complex to carry on towards the NNW, meeting the coast just to the south of Girvan.

The western parts of the area are accessible from the coast road from Girvan to Ballantrae, while the southern and eastern regions can be reached conveniently by the inland road from Girvan via Colmonell to Ballantrae. The inland road follows the north-eastern limits of the complex to the north of the River Stinchar.

Access to the central parts of the area is by two minor roads, the one from Lendalfoot to Garnaburn and the other from Lendalfoot via Laigh Knockclaugh to Pinmore on the main inland road.

The rocks which are involved in the complex include spilitic lavas associated with tuffs, agglomerates and radiolarian cherts. The intrusive members are predominantly ultrabasic rocks and a varied assemblage of basic rocks. Acid and intermediate rocks are developed on a minor scale and are confined to the north-western part of the area.

Metamorphic rocks mainly derived from basic igneous rocks by dynamic and thermal metamorphism are widely distributed.

A widespread mantle of superficial deposits often obscures the relations between various members of the complex, while extensive brecciation and alteration has affected almost all the rocks.

The general trend of the rocks, like that found elsewhere in the Southern Uplands, is NE-SW.

The central parts of the complex are mainly rough moorland country with an average height of about 500 feet. The more undulating ground is frequently occupied by the ultrabasic rocks, while lavas, gabbros and granites form prominent hills, the highest of which is Grey Hill (974 feet).

The drainage pattern conforms to two main directions: the main valleys including the Stinchar and Lendal Water, following the general NE-SW trend of the complex, the tributaries mainly belonging to a transverse system draining from the higher ground.

II. HISTORY OF RESEARCH

Nicol (1844, p.31) was apparently the first to refer to the Ballantrae igneous rocks and observed the occurrence of serpentinite north of Ballantrae.

During a study of the sedimentary rocks Murchison (1851, p.153) recognised the presence of eruptive rocks, and compared the ultrabasic rocks with those of the Lizard in Cornwall.

The earliest detailed petrographic study of the igneous rocks was made by James Geikie in 1866 who, with the assistance of Archibald Geikie, Young and Peach, produced the first map of the area in 1867. Geikie's interpretation of the origin of many of the igneous rocks was severely criticised by Murchison and Forbes (1867). His contention that many of the rocks were altered sediments and not true igneous rocks was presented in the Geological Survey Memoir of the district in 1869.

Heddle (1878) described some diallagic gabbros which crop out on the shore north of Lendalfoot.

Bonney (1878) examined the rocks studied previously by Geikie and came to the conclusion that they were all igneous in origin and included lavas and intrusive rocks. The lavas he regarded as being Old Red Sandstone in age and the ultrabasic rocks he assigned to the Carboniferous (op.cit., pp.783-784).

The presence of fragments of volcanic rocks in a Caradocian conglomerate (Kirkland) which crops out in the area suggested to Lapworth (1882) that the igneous rocks might correspond in age to the Arenig and Lower Llandeilo volcanic rocks of Wales and the Lake District. He regarded the ultrabasic rocks as possibly post-Silurian in age.

In 1889 Lapworth was able to confirm the Arenig age of the volcanic rocks at Bennane Head, north of Ballantrae, by the discovery of Middle Arenig graptolites in black shales intercalated with pillow lavas (op.cit., p.22).

A complete re-survey of the district was undertaken by A. Geikie, Peach and Horne, the revised edition of the area (Sheet 7) appearing in 1898 and this has not yet been superseded to the present day. The related publication of a Geological Survey Memoir, "The Silurian Rocks of Britian: Vol.1, Scotland" in 1899, which includes petrographic notes by Teall, presents a very complete account of the state of knowledge at that time.

A short summary of the results of the re-survey was given previously by A. Geikie (1897) in "Ancient Volcanoes of Great Britain, Vol.1".

Peach and Horne (1899) concluded that the ultrabasic rocks were the earliest intrusions and cut the lavas, tuffs and agglomerates (op.cit., pp.437, 465-466, 469, 471). A later series of basic rocks intruded the ultrabasic rocks and exhibit chilled margins towards the latter (e.g. Lendalfoot).

A group of metamorphosed basic rocks occurs in association with the ultrabasic rocks in some areas. Those cropping out on Littleton Hill were described by Teall (1899, pp.477, 479-480). He regarded them as thermally altered and recrystallised diabase-porphyrite lavas. A similar group of altered basic rocks was described from the neightbourhood of Millenderdale. Teall also made some observations on the basic and acid intrusive complex of Byne Hill (op.cit., pp.481-483).

Mellard Reede (1900) records an analysis of serpentinite together with some radiolarian cherts.

A further study of the metamorphosed basic rocks at Littleton Hill was made by Mort (1909) who regarded them as dynamically altered intrusive rocks.

Tyrrell (1909) also maintained that they were originally intrusive rocks and regarded them as an earlier basic rock series, overwhelmed and thermally metamorphosed by the peridotite, now serpentinized. By virtue of their texture, which is strongly granulitic, they have been grouped in the present account under the general name of "granulite".

A comprehensive account of the igneous complex was presented by Balsillie in 1932. The granulitic rocks he regarded as derived from basic intrusions occupying "rifts" in the peridotite which, tending to close up on the still hot basic rock, resulted in their reconstitution (op.cit., pp.122-123).

Pringle (1933, pp.57-58) suggested the possibility of the ultrabasic rocks and associated basic intrusions being pre-Cambrian in age, an observation contested strongly by Tyrrell (1933, p.59) who pointed out the similarity of the spilite-serpentinite association in the district with that in other parts of the world. However, Pringle's views are set forth in the Geological Survey Regional Handbook for the South-West of Scotland (1935 and 1948, p.9).

Anderson (1936) described a contact at Pinbain between Arenig lavas and serpentinite from which he inferred the latter to be intrusive. The evidence is inconclusive however since the contact is probably not an original one (see Beveridge, 1950, p.61; Bailey, 1952, p.33; this thesis p.29).

Like Tyrrell he pointed out the similarity of the igneous complex with the typical "ophiolite" and "radiolarite-serpentinite" assemblages of ancient geosynclines, the members of which are closely associated in space and time.

In 1937 Balsillie published the results of further study of the granulitic rocks, modifying some of his earlier (1932) observations. He regarded the whole of the southern outcrop of ultrabasic rocks as having undergone regional metamorphism with the production of the granulitic rocks from basic rocks intrusive in the earlier ultrabasic series. From the lack of any metamorphic effects in the serpentinite he inferred that its serpentinization post-dated the regional metamorphism (op.cit., pp.23-24).

Balsillie concluded that the ultrabasic rocks, together with many of the altered basic intrusives (granulites) were pre-Cambrian in age. He based his view largely on his discovery of glaucophane-schists and "ecologite" which he regarded as "interbanded" with the adjacent serpentinite. The presence of a general N-S or NW-SE foliation in the serpentinite was, he thought, further evidence in support of a pre-Arenig age for that member of the complex since no comparable trend could be demonstrated in the Arenig lavas.

Anderson (1937, p.188) denied the existence of a NW-SE foliation in the serpentinite. He was also unconvinced that any part of the serpentinite could be regarded as highly metamorphosed, although highly metamorphosed rocks occur in association with it.

Beveridge (1950) made a petrological study of the rocks over an area of 5 square miles in the region of Colmonell. He concluded that the serpentinite is probably intrusive into the spilitic lavas and that the serpentinization of the ultrabasic rocks occurred after their consolidation. The dolerites and granulitic rocks are all intrusive into the ultrabasic rocks, granulitization being a late consolidation effect, due to "the peculiar conditions under which the rocks crystallized". The main agents causing granulitization were pneumatolytic gases and "serpentinization pressure" (op.cit., pp.61-63). Several new rock analyses were presented, some of which are quoted in the present account.

His conclusions relating to the origin of the granulitic rocks are similar to those reached by Balsillie.

A historical account of previous research in the Girvan-Ballantrae district was presented by Bailey and McCallien (1952) who also introduced a new interpretation of the origin of the ultrabasic rocks, regarding them as submarine lavas extruded during the Arenig volcanic period.

III. STRATIGRAPHY AND GENERAL STRUCTURE OF THE COMPLEX

The base of the Arenig volcanic series is nowhere exposed and its upper limit is similarly unknown, although it is clearly pre-Bala.

The igneous rocks suffered post-Arenig folding and erosion, the Bala sedimentary rocks which are composed largely of detritus from the igneous complex, lie unconformably upon the Arenig series.

Post Ordovician sedimentary rocks include the Silurian and Old Red Sandstone both of which suffered Caledonoid folding and faulting, the trend of which is NE-SW. A small development of Permian sandstone is exposed on the shore north of Ballantrae.

The succession of the formations in the area to be described is:

Permian		
~~ U		
Old Red Sandstone		
~~ U		
Silurian		
~~ U		
Drummuck Group Barren Flags Whitehouse Group Ardwell Group Balclatchie Group	Ardmillan	Bala
Benan Conglomerate Stinchar Limestone Kirkland Conglomerate	Barr	Bala
~~ U		
Ballantrae Igneous Series (Base Unknown)		Arenig

IV. VOLCANIC ROCKS

1. Lavas.

(a) Distribution:

As shown on the map (Plate 1) the lavas occur in three main belts; the northern, central and southern belts.

The northern belt occupies the shore from Pinbain to Kennedy's Pass extending inland along the flanks of Grey Hill and covered unconformably by the Benan conglomerate to the north.

The central belt forms the largest continuous exposure and extends inland from Bennane Head a distance of some 6 miles to the NE where it disappears beneath the Benan conglomerate.

The southern belt of lavas is less continuously exposed, being obscured by the alluvium of the River Stinchar and faulted against younger greywackes forming the southern boundary of the igneous complex.

(b) Field Relationships:

The lavas are generally in contact with ultrabasic rocks but occasionally with basic rocks which locally intervene against the ultrabasic rocks.

Along the margins of the spilitic rocks there has been intense shearing and brecciation affecting the lavas and adjacent rocks. On the northern flanks of Carleton Hill and north-eastwards to Loch Lochton the shearing has rendered the lavas and associated rocks schistose (Peach and Horne, op.cit., pp.456-459, 473).

(c) General Characters of the Lavas:

The rocks are quite typical of the majority of British Palaeozoic spilites. Pillow structure is a common feature and the association of the lavas with radiolarian cherts and mudstones indicates that they were submarine.

Generally the rocks are greenish in colour and fine grained although strongly porphyritic varieties are not uncommon (e.g. Knockdolian Hill). They show only a vague tendency to a variolitic texture, the term "sub-variolitic" being applied to them by Balsillie (1932, p.110). See Plate 11.

The rocks always contain abundant microlites of soda plagioclase dispersed throughout a green chloritic groundmass in which a glassy mesostasis is frequently present. A flow banding is sometimes developed, felspar microlites being tangentially disposed about more porphyritic individuals or calcite-filled vesicles.

Study of the soda plagioclase reveals, in the majority of cases, that it is secondary in origin. This is particularly well demonstrated in the larger porphyritic plagioclase crystals where alteration to a saussuritic aggregate suggests the original felspar was calcic.

Only occasional relics of pyroxene are preserved, the majority being completely chloritized.

Iron ore is always abundant.

The frequent occurrence of precipitated limestones associated with the lavas and some of the altered basic intrusives are regarded by the writer as representing some of the lime removed from the basic rocks during the process of albitization (see p. 113).

It is concluded that albitization was a late stage hydrothermal effect (Eskola, 1935, p.2).

2. Pyroclastics.

(a) Distribution:

Agglomerates and tuffs are associated with the lavas in all areas and locally predominate over the lavas (e.g. Bennane Head, Knockdolian Hill).

(b) Field Relationships:

The pyroclastic rocks are interbedded with the lavas and help to demonstrate the high degree of folding and deformation to which the lavas have been subjected. At Bennane Head large recumbent folds can be seen in the agglomerates and tuffs which are associated with lavas and radiolarian cherts.

The pyroclastic rocks frequently crop out in lenticular masses with a NE-SW trend, conforming to the general trend of the complex.

(c) General Characters:

In the majority of cases the pyroclastic rocks are composed largely of spilitic material.

Balsillie (1937, p.32) has listed the following rock types from an agglomerate in the central belt of lavas about 600 yards E of South Ballaird: gabbros, sheared gabbros, dolerites, spilites and metamorphosed basic rocks (granulites) together with "serpentinous fragments". The present writer has confirmed Balsillie's observations with the exception of the "serpentinous fragments" which could not be definitely identified.

This assemblage is regarded by Balsillie as indicating that the ultrabsic rocks, and many of the metamorphised intrusives are older than the entire suite of Arenig volcanics.

Bailey (1952, p.33) has found fragments of glaucophane-schist in an agglomerate exposed on the shore at Pinbain.

3. The Age of the Lavas and Pyroclastic Rocks:

Following Lapworth's discovery of Middle Arenig graptolites at Bennane Head, several other graptolitic localities were discovered by Peach and Horne all of which are associated with lavas or pyroclastic rocks

(1899, pp.436, 439, 440, 442-444, 458-459).

While the age of the central belt of lavas is Middle Arenig (Bennane Head), there is the possibility that the northern belt of lavas from Pinbain to Kennedy's Pass is slightly older (op.cit., pp.442-444).

The age of the southern belt of lavas cannot be demonstrated due to the lack of fossil evidence.

V. ULTRABASIC ROCKS

1. Distribution:

Intrusive rocks of an ultrabasic composition form the largest and most widespread member of the intrusive series (Plate 1).

Their outcrops are largely confined to two NE-SW trending belts each with an average width of 1 mile:

(a) The northernmost belt occupies the shore between Pinbain and Lendalfoot, extending inland for a distance of 4 miles. Continuous with this belt to the SW is a smaller, more irregular area of ultrabasic rocks.

(b) The southern belt has a more extensive outcrop some $1\frac{1}{4}$ miles to the south and attains a length of some 6 miles.

The two ultrabasic belts are separated by the lavas and associated basic rocks which crop out from Bennane Head north-eastwards to Millenderdale. A small lenticular mass of ultrabasic rocks occurs at Knockormal in the central part of this belt of lavas.

A dyke-like body of ultrabasic rock is associated with the southern belt of lavas at Breaker Hill.

2. Field Relationships:

A. Peridotitic Masses:

The paucity of critical exposures renders difficult the determination of the relations between the ultrabasic rocks and those with which they are in contact. Moreover, not only are the ultrabasic rocks invariably serpentinized but, with few exceptions, notably at Byne Hill and Lendalfoot, exposed contacts are evidently planes of movement.

Rocks marginal to the ultrabasics are, for the most part, lavas. Exceptions to this occur mainly in the northern belt where basic rocks form the northern boundary for a distance of 2¼ miles, while the southern margin is partly occupied by schistose rocks (Plate 1 and pp.10,38).

The southern margin of the southern belt of ultrabasic rocks is largely obscured by later deposits of the River Stinchar. However, Peach and Horne regard at least part of the margin as tectonic (Plate 1).

Table 1: Ultrabasic Rock Types Developed in the Complex in Addition to Harzburgite.

Dunite (with subsidiary Pyroxene)	Lherzolite	Chromitite (with gradational Chrome-Dunite)	Wehrlite	Pyroxenite including: Diallagite Bronzitite Websterite
Knockdhu N. Ballaird Poundland Burn	Lendalfoot	Poundland Burn	Knockormal Breaker Hill	Knockormal Lendalfoot Pinbain Breaker Hill

Evidence of cataclasis is displayed in the marginal lavas at Knockdaw Hill on the northern margin of the southern belt.

While the main trend of the ultrabasics is NE-SW, in the region of North Ballaird and Burnfoot the margins of the ultrabasic rocks appear to cut across the NE-SW structures developed in the adjacent lavas and tuffs, but exposures are so poor that little detailed information can be obtained.

B. Ultrabasic Dykes:

Intrusive into the main peridotite masses are a group of pyroxenite dykes, one of which appears also to intrude the lavas at Breaker Hill (P.28).

3. Petrography:

The prevalent rock type in all areas is a serpentinized harzburgite (olivine-enstatite rock). Minor developments of less serpentinized ultrabasics are summarized in Table 1, together with their localities.

A. Peridotitic Masses:

(a) Serpentinized Harzburgite:

These rocks maintain an extremely constant mineralogy over large areas and are those rocks referred to as serpentinite in this account.

Although the olivine is generally completely serpentinized unaltered pyroxene often remains, but some replacement by antigorite (bastite) can always be observed.

The rock breaks easily and has an almost sub-conchoidal fracture. The colour is dull black or deep bottle-green and some surfaces have a greasy appearance. Conspicuous in the dull serpentinous groundmass are randomly oriented, porphyritic crystals of glittering, sub-metallic bronzite.

Thin veins of chrysotile can generally be seen while greenish chrysotile also occupies fractures or joints in the rock and exhibits slickensided surfaces produced by subsequent movement.

Under the microscope no unaltered olivine remains although its former presence is indicated by pseudomorphous cores of colourless or pale yellow, sub-isotropic serpophite. These cores have a dusty appearance due to the presence of minute magnetite granules, often arranged in parallel streaks simulating cleavage (cf. p.22).

Each serpophite core is surrounded by a partially continuous rim of granular magnetite which imparts the typical "mesh-structure" to the rock in thin sections. Outwith this, enclosing the serpophite and magnetite, is a partially encircling rim of vein-like cross-fibre antigorite, the central part of each vein being occupied by a streak composed of minute magnetite granules. Other antigorite veins form as off-shoots from the main circular veins and ramify through the rock, uniting with other veins and producing a complex anastomising background to the predominant "mesh-structure" defined by the serpophite and magnetite.

Large platy bronzite crystals are set in the serpentinous groundmass and are frequently intersected by antigorite veins. All stages in the replacement of the bronzite by the pseudomorphous bastite can be observed and are generally accompanied by the development of secondary schiller-like magnetite.

Irregular bodies of deep chestnut-brown picotite are a constant accessory (Plate 12, A, B).

Serpentinite cropping out on the shore at Burnfoot differs in the development of a dark reddish-brown colouration in hand specimen.

Under the microscope it can be seen that this is brought about by the conversion of magnetite to haematite, although in all other respects the rock is identical to the typical serpentinite described previously. So complete is the haematitization that even the fine magnetite "dust" in the serpophite is haematized (Plate 12, C.).

It is quite clear that, although the rocks have been almost completely serpentinized, the original textural relationships and, in the case of the bronzite, crystal boundaries, are perfectly preserved. That the serpentinization of the rocks has been one of pseudomorphism precludes large changes in volume during the process of serpentinization. Further examples will be given subsequently.

(b) Serpentinite with Flow-Structure:

Rocks of this type are indistinguishable in hand specimen from those previously described and the extent to which they are developed is uncertain. Four specimens have been obtained from widely separated localities in the southern belt.

A marked linear flow-structure is exhibited in the micro-texture of the rock which is a completely serpentinized harzburgite.

Serpophite cores after olivine tend to be slightly elliptical with the major axes parallel to the general direction of flow while the surrounding rim of magnetite granulte assumes the same form. Veins of cross-fibre antigorite define the structure more strongly since they form long delicate veins parallel to the longer axes of the serpophite cores (Plate 13, A).

The structure is therefore likethat of "mesh-structure" serpentine affected by directed pressure producing an elongation of the members while yet generally preserving their mutual relationships.

That actual flowage has occurred is suggested by the way in which the flow-structure is deflected around large bronzite crystals which show no signs of cataclysis or bending, even when the cleavages lie at right angles to the direction of flowage.

Post-dating the main flow structure are a few sub-parallel veins of cross-fibre antigorite.

(c) Serpentinite with Mineral Banding:

A small exposure of serpentinite on the north-eastern flank of Cairn Hill exhibits mineral banding produced by alternating bands of altered olivine with others of ore and pyroxene, a structure which is probably to be regarded as primary (Plate 13, B). The trend of the banding is NW-SE, the planes dipping at a high angle to the SW.

Balsillie regarded this as evidence that the ultrabasic rocks, unlike other members of the complex, possess deformation structures trending NW-SE. He appears to have regarded the mineral banding as having similar significance to schistosity (1932, p.115; 1937, p.29). This is one of Balsillie's main reasons for believing the serpentinite to be pre-Cambrian in age.

Like Anderson (1936), the present writer could find no evidence of a NW-SE schistosity in the ultrabasic rocks whereas a NE-SW foliation or shearing is frequently exhibited, especially along the margins with other members of the complex.

(d) Dunite:

The rocks are black in hand specimen with an irregular fracture and the texture is xenomorphic-granular. Black grains of fresh olivine are outlined by a greyish intergranular matrix of soft serpentinous material. Pyroxene is quite subordinate in amount.

In thin sections the granular olivine individuals are clearly defined, fresh kernals surrounded by the typical "mesh-like" magnetite and antigorite veinlets are abundant. Many of the relict olivine kernals have formed parts of a larger individual since a great many extinguish simultaneously.

The optical properties of the olivine are: Ny = 1.712[x];

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[x] All refractive indices are referred to Na_D light unless stated otherwise and are accurate to ± 0.002.

2Vx = 87^{o}; the composition being Fo_{75} Fa_{25} (Winchell, 1951, p.500).

A noticeable feature of the olivine kernals is the presence of tiny parallel streaks composed of minute magnetite granules, presumably lying parallel to a faint cleavage. It seems probable that these fine bands of ore represent the break-down of the olivine since they are accompanied by a fall in the birefringence of the olivine (cf. Foslie, 1931, p.222).

The margins of the partially altered olivines are encircled by a narrow zone of cross-fibre antigorite beyond which occurs sub-isotropic serpophite (Plate 14, A,B.).

In some of the areas between the olivine or its pseudomorphs there are irregular but roughly rectangular bodies composed of a matte of interlacing tremolite fibres. These may represent a clinopyroxene, since the commoner types of serpentinite orthopyroxene has generally been replaced by antigorite (bastite).

Primary grains of picotite are present in xenomorphic aggregates.

These rocks are best described as partially serpentinized, pyroxene-bearing dunites.

(e) Chromitite:

Veins and segregations of almost pure picotite-rock are common in the serpentinized dunites near the head of the Poundland Burn (Peach and Horne, op.cit., p.468).

All gradations exist between dunite, through chromiferous dunite, to pure chromitite. Indeed, except for the more pyroxene-rich varieties, there are few specimens of ultrabasic rock that do not carry some picotite.

(f) "Picrite":

Teall (1899, pp.469-470) described a rock from the summit of Breaker Hill as a hornblende-picrite. The same rock was redescribed by Balsillie (1932, p.112-113) who claimed that it could be traced southwestwards to Poundland Burn, a distance of 1 mile. The present writer was unable to trace the rock for more than a few yards.

In hand specimen the rock appears at first glance to be a normal serpentinite. Closer inspection however reveals that in addition to the predominant dark greenish-black serpentine there is a while substance which is easily scratched with a knife.

Teall's description of the rock in thin section is as follows, "Serpentine derived from olivine, with the unaltered mineral still preserved in the cores of the rock. The augite is nearly colourless and occurs both in the form of large plates and as granulitic aggregates. The hornblende is perculiar as regards its colour and pleochroism, (X), colourless (Y) and (Z), rich but not very deep brown and with only slight differences. Biotite is not present in any considerable amount. It occurs as aggregates of small scales, and possesses the same colour as the hornblende".

A white, semi-opaque substance occurs which strongly resembles saussuritized felspar and was so designated by Teall, but the presence among the alteration products of zoisite (?), granules of magnetite and brown hornblende suggests that the original mineral was pyroxene (Plate 14, C.). The alteration would thus be analogous to that displayed by the clinopyroxene in the wehrlite to be described subsequently (p. 26).

B. Ultrabasic Dykes:

(a) Lherzolite:

Olivine-enstatite-diallage rock forms a prominent feature rising above the boulder strewn shore about 50 yards to the NE of Lendalfoot. It is a dyke cutting and including fragments of the adjacent serpentinite.

In hand specimen the rock shows conspicuous shining plates of pyroxene which average ¼" in size and stand out against a darker background composed largely of olivine and ore.

The texture is poikilitic with rounded olivine crystals enclosed by enstatite, the latter sometimes being enclosed in turn by large fibrous plates of diallage. Olivine also occurs in the large intergranular areas between the pyroxenes (Plate 15, A.).

Most of the olivine has been serpentinized except for those crystals poikilitically enclosed in the pyroxene.

The enstatite is partly altered to bastite or a fibrous uralitic amphibole which tends to develop along the original cleavage planes. Like the olivine, crystals of enstatite enclosed by the diallage are unaltered.

The diallage is quite unaltered except for a little chlorite and iron ore.

(b) Wehrlite:

Olivine-diallage rock (S.G. 3.375) and associated pyroxenite is intrusive into serpentinite at Knockormal.

Macroscopically the rock is dark greenish-grey, hypautomorphic-granular and varies in grain size up to 1 to 1.5 m.m. (Plate 15, B, C.).

The pyroxene is more euhedral than the olivine which tends to form smaller interstitial grains and is optically identical with that in the dunites (p. 21). The pyroxene is a colourless diopsidic variety (diallage) with the following optical properties: $2V_z = 56^\circ$; $Z:c = 38^\circ - 40^\circ$;

birefringence 0.025 and a good (100) parting.

Even when the olivine is completely serpentinized the pyroxene often remains quite fresh apart from a few replacement veinlets of chrysotile, but sometimes develops a fine dusting causing the crystals to become whitish and transulscent or semi-opaque under the microscope. Simultaneously the birefringence falls to around 0.008 resembling highly saussuritized felspar (cf. Benson, 1914; Turner, 1930, p.187).

This alteration appears to results from liberation of iron from the pyroxene molecule and is thus analogous to the development of tiny granules of ore in the olivine at the onset of serpentinization (p. 22).

In the more serpentinized rocks there occasionally occur rounded bodies of an opaque ore mineral, the central parts of which consist either of a deep olive-green spinel (ceylonite) or brown picotite.

(c) Pyroxenite:

The Knockormal wehrlite apparently grades into an olivine-free pyroxenite (S.G. 3.201), although the precise relationships between the two rocks are obscure.

The rock consists of a coarsely lamellar aggregate of pearly grey pyroxene. In places the rock has undergone deformation causing granulation of the pyroxene.

In thin sections the pyroxene is a colourless diopside:

$2V_z = 60^{\circ}-62^{\circ}$; $Z:c = 41^{\circ}$ and a strong (100) parting together with occasional polysynthetic twinning parallel to (001). The crystals are frequently bent and exhibit undulatory extinction (Plate 16, A.).

Pyroxenite is intrusive into serpentinite $\frac{3}{4}$ mile to the north of Lendalfoot (cf. Heddle 1878, p.778; Bonney, 1878, p.464).

This rock is the coarsest-grained of all the ultrabasic rocks in the complex. Deep green or black plates of diallage are abundant in large, interpenetrating, matted clumps; while smaller crystals of metallic bronzite can also be distinguished. Within a few inches, and quite irregularly, complete variation from diallagite through websterite to bronzitite occurs.

Thin sections show dispersed patches and veinlets of talc together with intergranular areas of fibrous tremolite. Some of the orthopyroxene is converted to bastite. The pyroxene also alters to a beautiful ultramarine chlorite which is probably chromiferous and related to kammererite.

Table 2: Analyses of Serpentinite and Bastite from the Girvan-Ballantrae Complex.

	1.	2.	3.	4.
SiO_2	38.58	40.04	38.29	37.776
TiO_2	0.04	-	-	-
Al_2O_3	1.65	0.40	3.95	2.123
Cr_2O_3	0.24	0.39	-	-
Fe_2O_3	3.94	5.77	2.53	5.069
FeO	2.49	1.91	4.04	2.095
MnO	-	-	-	0.076
MgO	37.84	37.26	35.55	37.014
CaO	0.04	-	0.57	-
Na_2O	0.62	-	-	tr
K_2O	0.11	0.60	-	
H_2O +	12.68	13.42	14.08	16.07
H_2O -	1.49	-	-	-
P_2O_5	0.04	-	-	-
FeS_2	0.10	-	-	-
NiO	0.06	-	0.15	-
CO_2	0.10	-	-	-
	100.02	99.79	99.16	100.223

1. Bastite-serpentinite, Balhamie Hill (Balsillie, 1932, p.113).
2. Serpentinite, Byne Hill Burn. (Reed, 1900, p.111)
3. Bastite-serpentinite, Balhamie (Bonney, 1878, p.771).
4. Bastite, Balhamie (Heddle, 1878, p.494).

A dyke-like mass of websterite appears to intrude lavas at Breaker Hill (Plate 1). The mass is about 20 feet wide and weathers to an ochrous colour. The precise junction with the lavas is not exposed but is evidently a line of movement along which the websterite is rather sheared (Plate 3, C.).

In thin sections the diallage, which is optically identical with that in the wehrlite, appears quite fresh apart from occasional serpentinous veinlets.

Pseudomorphs after enstatite, often enclosed in large diallage plates, makes up the remainder of the rock (Plate 16, B.).

4. <u>Analyses</u>:

No new analyses of the ultrabasic rocks or their constituents have been made in connection with the present study, but four analyses made by previous workers are given in Table 2.

5. <u>Deformed Serpentinite</u>:

A considerable amount of shearing and slickensiding occurs along the margins of the serpentinite, but true schistose serpentinites (tremolite schist) are never developed.

An example of this deformation is well exposed at Burnfoot near the seaward side of a wall that surrounds the most westerly cottages by the shore. The movement appears to be associated with a NE-SW fault which separates the serpentinite from the lavas and tuffs to the south.

The strongly sheared material is quite rotten and earthy-looking but it encloses and wraps around ellipsoidal boulders of a massive serpentinized harzburgite (Plate 3, A). Together with the massive serpentinite there occur cobbles of altered gabbro derived from small dykes, similar to those cutting unmoved serpentinite nearby (Plate 3, B).

6. Contact and Marginal Phenomena between lavas and Ultrabasics.

(a) Pinbain:

Anderson (1836) claimed that an exposure of spilite on the shore near the mouth of the Pinbain Burn was intruded by the ultrabasic rocks. Later however Beveridge (1950) and Bailey (1952) concluded that this contact might well be interpreted as secondary in origin, involving the intrusion of spilite by the serpentinized ultrabasic rocks. The same conclusion has also been reached by the present writer.

The contact occurs along the margins of a small knob of lava, with vague pillow structure, projecting above the sand. The exposure is isolated from the main outcrop of lava a few yards to the north. It is not easy to follow the contact in detail since the lava is itself serpentinized and rather brecciated.

The evidence indicates that the contact is not simply marginal but appears also to pass over the top of the mass. It may well be that the outcrop represents an inclusion in the serpentinite and is not part of the main mass of lavas nearby.

In thin sections spilitic texture is developed while most of the plagioclase has been converted to zoisite. Pyroxene is remarkably fresh and is strongly titaniferous.

As the contact with the serpentinite is approached the pyroxene becomes altered to "saussuritic" looking aggregates of dusty epidote, while the groundmass becomes invested with thorn-like antigorite (cf. p.85).

Within a few inches the serpentinized spilite grades into serpentinite, passing through a rather brecciated phase near the actual junction.

Veinlets of cross-fibre antigorite and chrysotile leave the serpentinite and branch intrusively into the spilitic rock (cf. Anderson, op.cit.).

It is quite clear therefore that the lava has suffered replacement by serpentine along its margins.

(b) Knockormal:

Spilitic lavas marginal to a lenticular outcrop of ultrabasic rocks at Knockormal are highly brecciated and, as the ultrabasic margin is approached, actinolitic amphibole develops at the expense of chloritic alteration products in the lava, the original texture being preserved (Plate 11, C.).

In cases where the lavas have been brecciated there is an abundant development of quartz-epidote veins, often accompanied by fibrous actinolite. Sporadic developments of red jasper associated with the lavas are derived from radiolarian cherts which have been largely recrystallized into a fine-grained quartz mosaic with abundant haematite.

Idential relationships exist in the marginal lavas at North Ballaird to the SW.

In neither case has an actual contact with the serpentinite been observed.

(c) Breaker Hill:

The dyke-like body of websterite associated with the lavas was regarded by Peach and Horne (op.cit., p.470) as an offshoot from the main southern belt of ultrabasic rocks adjacent to Breaker Hill. They do not appear to have recognised the distinctive mineralogy of the rock, and refer to it as "serpentinite" (cf. Anderson, 1936).

The present writer could find no evidence of continuity between the dyke and the serpentinite.

It is concluded, therefore, by analogy with similar rocks at Lendalfoot and Knockormal, that the websterite is later than the main mass of serpentinite and can only be interpreted as a dyke cutting the lavas.

Like the previous examples the marginal lavas are rather brecciated and carry abundant quartz-epidote veins while pyrites is developed along one of the margins. No actual contacts are exposed.

7. Interpretation of the Contact Phenomena:

There is no indication that the lavas have been subjected to high temperature contact metamorphism such as would be expected in proximity to a peridotitic mass of such dimensions. Evidence of low temperature hydrothermal alteration and replacement is, however, general.

It is well known that many ultrabasic masses in various parts of the world produce little contact alteration of the invaded rocks (cf. du Rietz, 1935), while on the other hand conversion of sedimentary rocks to diopside-hornfels at an ultrabasic contact has been recorded by Ingerson (1928). Other examples of contact metamorphism are numerous.

The lack of significant metamorphism in the Girvan-Ballantrae lavas can be accounted for in two ways:

(a) The ultrabasic magma was intruded at a very low temperature or, (b) it was intruded at a high temperature but the original contacts are not exposed.

(a) With the possible exception of the pyroxenite dyke at Breaker Hill, there is no evidence to support a low temperature of intrusion of the peridotite masses.

(b) Basic rock inclusions in the serpentinite will be considered subsequently which have suffered striking thermal metamorphism during their envelopment in the original peridotitic magma (p. 60), while adjacent outcrops of lava are unmetamorphosed. It is concluded therefore that during its initial intrusion the ultrabasic magma was at a high temperature but during its serpentinization it was squeezed upwards in a "cold" semi-plastic state, probably along dislocations which were the upper extensions of those along which the original magma was intruded at depth.

The mobility of the serpentinite during its intrusions is demonstrated by the flow-structure which it develops. Furthermore, basic rocks which post-date the peridotitic rocks are serpentinized and intruded by the serpentinite (p. 85).

In addition one must bear in mind that the great majority of ultrabasic contacts have suffered post-serpentinite deformation and movement which obscures the relationships.

Taliaferro (1943) has recorded several instances of the "cold" intrusion of serpentinite in California while similar observations have been made in Cuba by Rutten (1936) Thiadens (1937) and Vermunt (1937).

8. <u>The Age of the Ultrabasic Rocks:</u>

In view of the conclusions reached in the previous discussion it is difficult to date the intrusion of the original peridotite in relation to the lavas.

However the pyroxenite dykes which intrude the lavas and ultrabasic rocks probably followed closely upon the intrusion of the main peridotitic masses (cf. Hess, 1938; Little, 1949; Walton, 1951; Proud and Osborne, 1952).

Further evidence relating to the age of the ultrabasic rocks will be presented subsequently (pp. 39, 96).

9. <u>The Form of the Ultrabasic Masses;</u>

It is extremely difficult to reach any definite conclusions as to the general form of the main ultrabasic masses.

The disposition of the two main ultrabasic belts on the map (Plate 1) suggests that they occupy the cores of two NE trending folds followed (stratigraphically) by the lavas forming outcrops at Pinbain, Bennane Head and Downan Point.

On this basis (cf. Peach and Horne, op.cit., p.449) Bailey (1952, p.15) interprets the succession and structure as two NE trending anticlines comprising the (Lower) Knockdolian Spilitic Group; Ballantrae Serpentinite and (Upper) Downan Point or Bennane Head Spilitic Group (Fig.1.).

It has already been indicated (p. 14) that the age of the Downan Point, or southern belt of lavas, is unknown while the northern belt of lavas may be slightly lower than Middle Arenig (Bennane Head).

Hence no definite equivalence exists between the lavas of Bailey's Upper Spilitic Group upon which his structural determination is largely based.

Bailey's interpretation also implies that the ultrabasic rocks form an essentially concordant body which he believes to be of an extrusive origin (cf. Stoppani, 1880). There is neither petrographic nor field evidence to support an extrusive origin for the ultrabasic rocks.

It is concluded that the ultrabasic masses occur either in the form of a sill or sills or as discordant upward prolongations from a deeper zone of ultrabasic rocks (cf. Proud and Osborne, 1952). The possibility that the ultrabasic rocks form large thrust slices can not be disregarded in view of the tectonic nature of their boundaries.

10. Affinities:

The ultrabasic rocks of the district exhibit close analogies, both in their petrology and general field occurrence, with ultrabasics characteristic of island arcs and "alpine mountains" (cf. Benson, 1926). They also possess many of the characters of the primary peridotite suite of Hess (1937, 1938), being quite distinct from those ultrabasic rocks originating as differentiates of basic intrusions.

Their association with submarine volcanics and geosynclinal sediments belonging to the "ophiolite" and "radiolarite-serpentinite" assemblages is also typical and widespread (cf. Stoppani, 1880; Jehu and Campbell, 1917; Stanb, 1922; Steinmann, 1926).

While many ultrabasic rocks are associated with submarine lavas and sediments this no more implies that they are extrusive than does the association of ultrabasic rocks with surface lavas in which an intrusive origin is generally accepted.

VI. BASIC IGNEOUS MASSES AND THEIR METAMORPHIC DERIVATIVES

1. Introduction and Classification.

(a) Distribution and Form:

Basic masses, principally gabbro and dolerite, are distributed throghout the area, mainly within the ultrabasics but also in the lavas. Many appear to be dyke-like (e.g. Lendalfoot) while others are boss-like, often only a few feet in size (Plate 1).

The largest mass is the gabbro which extends from Grey Hill to Byne Hill in the northern part of the area and has a continuous outcrop of over 3 miles. The precise form of this mass is uncertain.

Many of the basic masses are clearly intrusive into the ultrabasics, in other cases the relationship is obscure, while some are more easily explained as inclusions in the ultrabasics.

(b) Metamorphosed Basic Rocks:

(i) Thermally Altered:

These masses are demonstrably derived by the thermal alteration of gabbros and dolerites and in general have a hornfelsed appearance and a strongly granular texture. They are the most commonly developed metamorphic rocks and are referred to under the general heading of "granulite".

In addition to those granulites derived from basic intrusives there is evidence to suggest that some may have been lavas.

(ii) Dynamically Altered:

Not always clearly separated from (i) are rocks, often with a granulitic texture, which clearly owe their origin mainly to dynamic processes and exhibit transitions from fine grained partly schistose granulite to coarse flasered gabbros.

A small development of glauçophane-schist and "eclogite" has a more doubtful metamorphic history and may have formed under conditions of rather higher pressure than the granulitic rocks. These rocks are also derived from basic intrusives.

The narrow strip of sheared lavas and basic intrusives along the southern margin of the northern serpentinite belt has already been referred to (p. 10). These rocks have been sheared and in some cases rendered truly schistose by the effects of movement along the boundary between the serpentinite and basic rocks. The rocks have already been described by Teall (op.cit.) and Anderson (1936) and will not be described here.

(iii) Metasomatically Altered:

It is probable that all the metamorphic rocks have undergone metasomatism to a greater or lesser extent.

The effects of metasomatism are most clearly seen in a group of garnetized gabbros (rodingites) and carbonated ultrabasics. Much of the contact phenomena in rocks adjacent to the ultrabasics falls under this heading.

(c) Relationships with the Ultrabasics:

The majority of the junctions between the basic rocks and ultrabasics are lines of movement. Notable exceptions to this occur at Byne Hill and Lendalfoot.

On the basis of field and petrographic characters the basic masses can be divided into three main groups:

(i) Basic masses which antedate the emplacement of the peridotite. These rocks are all metamorphic in character (e.g. granulites). Based on their comparatively high grade of metamorphism and association with the granulites, the glaucophane-schists and "eclogite" are included here although their precise relationships to the ultrabasics are in doubt. They are, however, clearly at least of preserpentinization formation.

(ii) Basic masses postdating the peridotite, but antedating serpentinization, are the most widespread of the basic masses (e.g. Lendalfoot, Byne Hill). These rocks are generally unmetamorphosed except for those which have undergone metasomatism connected with the serpentinization of the ultrabasics. Others have suffered deformation and have been rendered schistose.

(iii) Unmetamorphosed basic rocks which postdate the serpentinite, including Tertiary dykes.

Since all those basic masses under (i) are metamorphic in character and possess distinctive features they are referred to as "Older Basic Rocks", while groups (ii) and (iii) which are largely unmetamorphosed are termed "Younger Basic Rocks".

2. Older Basic Rocks.

A. Glaucophane-Schist Assemblages

(a) Field Relations:

Near the farm of Knockormal glaucophane-schists are associated with a lenticular mass of serpentinite which is probably an extension of that cropping out at North Ballaird about ½ mile to the SE (Fig. 2).

Intrusive into the serpentinite near its NE termination is the dyke of wehrlite and pyroxenite already described (p.25). This dyke forms a marked ridge which can be traced south-westwards to the Lendalfoot road.

Occupying the ridge near the road is a mass of glaucophane-schist apparently elongated in a NE-SW direction. No contacts with the adjacent rocks are exposed, but from the form of the ground the adjacent rocks are probably ultrabasics.

In addition to glaucophane-schists a small mass of green-schist is exposed near the pyroxenite dyke while another outcrop of green-schist bearing glaucophane-veins occurs immediately to the NW of the main glaucophane-schist exposure.

Small lenticular or knob-like masses of crushed and altered gabbro are associated with the serpentinite, together with three exposures of granulite.

The ultrabasic and associated basic masses are enclosed on all sides by spilitic lavas and tuffs which have suffered extensive shearing and cataclasis along their margins with the ultrabasics. These margins are almost certainly lines of movement.

The deformation has rendered some of the marginal lavas schistose, the resulting greenschists being indistinguishable from those just mentioned. These rocks are developed mainly along the southern margin of the ultrabasics. Crushed and amphibolized lavas occur along the northern boundary and have been described previously (p. 30).

The schistose rocks exhibit considerable variations in the trend of their schistosity, which seldom agrees with the general trend of the complex.

(b) Petrography:

(i) Epidote - hornblende - schist:

These rocks, although carrying no glaucophane, are included here since they are interbanded with the glaucophane-schists into which they grade as rims of glaucophane develop around the green hornblende.

They are dark green in colour with a well defined schistosity and are medium to fine grained. Dark shining cleavage surfaces of the amphibole are easily distinguishable, together with yellow epidote.

In thin sections the schistosity is defined by elongated hornblende and epidote crystals. Frequently the hornblende builds larger porphyroblasts which act as augen around which the smaller individuals are deflected (Plate 17, A). Albite is absent or insignificant.

An analysis of a sample of this rock is given under 1, Table 3.

(ii) Epidote - hornblende - glaucophane - schist.

In the field these rocks cannot be distinguished from those of the previous group. There is little sign of a blue colouration in the rocks due to the subordinate nature of the glaucophane relative to hornblende.

Under the microscope the rock possesses an intimate nematoblastic fabric formed by elongated epidote, hornblende

Table 4: Optical Properties of Amphiboles from Knockormal.

	GLAUCOPHANE	HORNBLENDE
X	Colourless	Pale yellow or colourless
Y	Sky-blue	Olive-green
Z	Lavender	Smoky blue-green
Nx	1.645	1.635
Ny	-	-
Nz	1.654	1.657
Nz-Nx	0.009	0.022
OPTIC PLANE	PERP. (010), Z = b	PARALLEL (010), Y = b
EXT.	Y:c = 11°	Z:c = 28° - 31°
2Vx	0° - 18°	66° - 68°

and glaucophane crystals which wrap around occasional epidote and hornblende porphyroblasts. Albite is confined to sporadic xenoblastic grains.

The glaucophane occurs as xenoblastic individuals but more commonly in the form of rims around green hornblende. It is quite clear that the glaucophane is developing from the green hornblende and all stages can be observed in the change of colour from one to the other.

The crystallographic and optic orientations of the glaucophane relative to the green hornblende from which it is derived tend to be constant and is shown in Fig.3.

The commonest crystal forms developed by the glaucophane are the prisms (110), and rarely (001). They average 0.3 m.m. x 0.1 m.m. in size and contain numerous inclusions of epidote and sphene. Optical data for the glaucophane are given in Table 4 and an analysis under 1, Table 5. Optically the mineral resembles crossite, particularly in the position of the optic axial plane. Further discussion on the affinities of the Knockormal amphiboles will be given subsequently.

Green hornblende of the same type as that in the previous rock is abundant and, like the glaucophane, is strongly diablastic towards epidote and sphene. A partial analysis of this mineral gave: Al_2O_3 10.12%, Fe_2O_3 4.42%, FeO 11.77%, Na_2O 3.04% and K_2O 0.33% (Anal. W.H. Herdsman).

Table 5: Analyses of Knockormal Glaucophane and Comparative Amphiboles.

	1.	2.	3.	4.	5.
SiO_2	50.36	54.52	56.06	50.41	55.02
TiO_2	1.22	0.39	-	1.66	-
Al_2O_3	9.12	9.25	8.87	7.82	4.75
Fe_2O_3	4.18	4.44	2.38	8.73	10.91
FeO	10.34	9.81	10.60	10.81	9.45
MnO	0.36	0.46	-	0.14	tr
MgO	9.74	10.33	11.11	7.39	9.30
CaO	4.62	1.98	3.26	3.99	2.38
Na_2O	6.85	7.56	5.53	7.04	7.62
K_2O	0.46	0.16	0.57	0.57	0.27
H_2O +	1.78	1.78	1.83	1.17	-
H_2O -	0.72	-	-	0.10	-
	99.75	100.68	100.21	99.83	99.70
S.G.	3.186-3.213	3.119	3.136	3.206	3.126-3.160

1. Glaucophane, Knockormal (Anal. W.H. Herdsman).
2. " San Pablo, California. Blasdale (1902, p.327).
3. " Mt. Saleve. Kunitz (1930, p.246).
4. Crossite, Anglesey. Holgate (1951, p.792).
5. " Berkeley, California. Palache (1894, p.181).

Its optical properties are given in Table 4.

Pale yellow or colourless epidote is abundant together with a little calcite. The presence of tiny specks of ore cause many of the epidote crystals to assume a dusty appearance. Granular sphene, often in streaky elongate clusters, and of a deep resin-brown colour, is abundant. Patches of an almost isotropic spongy brown substance appears to be a kind of saussurite (Plate 11, B, C, Plate 18, A).

An analysis of this rock is presented under 2, Table 3.

Apparently interbanded with the schistose varieties is a coarse non-schistose glaucophane-bearing rock with a gabbroidal texture. Hornblende, with marginal glaucophane, builds large unoriented plates and is associated with large idioblastic crystals of epidote (Plate 18, B). Albite is fairly abundant in xenoblastic veins and aggregates.

The rock appears to be similar in mineralogy and texture to the "glaucophane-gabbros" of Brouwer and Egler (1952, p.18) and it is probable that the finer grained rocks previously described have been derived from such a rock under the influence of more shearing. Vague saussuritic aggregates suggest the former presence of felspar.

An analysis of this rock is given under 3, Table 3.

(iii) Garnet-bearing Glaucophane - Actinolite - Schist:

A small mass of garnet-glaucophane-schist crops out beside the rocks previously described although its relationship towards them is abscure.

The rock (S.G. 3.117) has an extremely fine even-grained schistosity defined by small fibres and sheaves of pale green actinolite and chlorite, glaucophane and sporadic pale pink garnet. Both the actinolite and chlorite are diablastic towards epidote and sphene (Plate 18, C). The actinolite is pleochroic in pale greens with $2Vx = 79^{o}$ and $Z{:}c = 19^{o}$.

The glaucophane in this rock is optically distinct from that in the previous rocks. The pleochroism is X = colourless, Y = pale blue and Z = pale lavender; $2Vx = 48^{o}$, birefringence 0.021 and $Z{:}c = 6^{o}$ with the optic axial plane parallel to (010). It is apparent that the optical properties of the mineral correspond to those of a "normal" glaucophane.

(iv) Greenschists with Glaucophane-bearing Veins and Bands:

In these rocks only the veins are regarded as characteristic, the host-rock being identical with the greenschists.

The rock (S.G. 2.991) is pale green in colour and schistose. The glaucophane veins are conspicuous in hand specimen as deep blue streaks running parallel to the schistosity.

Glaucophane is confined to sharply defined bands and its habit is strongly asbestiform, much resembling crocidolite. Optically however it is the same as that in the schist described under (ii). Individual fibres may exceed 3 m.m. in length while their breadth is of the order of 0.01 m.m. The fibres pass almost imperceptably along their length into an equally fibrous, moderately pleochroic actinolite, which may in turn pass into chlorite.

Large epidote crystals are scattered throughout the bands and contrast with the tiny dusty-looking epidote in the host green-schist. A striking feature of the epidote is its tendency to form spherulitic bodies consisting of radially arranged crystals disposed about a central core of what appears to be saussurite (Plate 19, A).

The epidote and amphibole are embedded in a fine grained albite mosaic riddled with tiny fibres of actinolite and occasionally of glaucophane.

Calcite is generally present together with haematite.

The remainder of the rock consists of albite, actinolite, chlorite and calcite (see (v)).

A metasomatic origin for the glaucophane-bearing veins or bands seems inescapeable.

(v) Albite - epidote - actinolite - chlorite - schist (Greenschist)

In hand specimen the rocks are identical with those in the last group but lack the bands of glaucophane.

The texture is defined by sub-nematoblastic albite with a little quartz in a schistose mosaic, together with fibrous actinolite and chlorite.

Calcite is generally present and much of the rock is permeated with dusty haematite (Plate 19, B).

There is no evidence to suggest that the greenschists have been derived from the glaucophane-schists by a process of retrogressive metamorphism.

(c) Alteration of the Glaucophane-Schists:

Many of the rocks have suffered the effects of crushing and exhibit cataclastic textures.

Where this occurs crystals of glaucophane can be seen to break down into a granular mosaic of albite shot through with actinolite and relict glaucophane. That the albite and actinolite are secondary is indicated by the fact that neither of these minerals can be detected in the uncrushed portions of the rock which may be only a few millimetres away.

Veins of prehnite are abundant both in the crushed and uncrushed schists and are entirely posterior to the formation of the schists. The prehnite is commonly riddled by tiny fibres of actinolite (Plate 18, A).

(d) Chemical Compositions:

The analyses of the Knockormal glaucophane-schists in Table 3 compare closely with Washington's basic group of glaucophane-schists derived from basic igneous rocks (1901). The Knockormal rocks carry rather more MgO and CaO, together with less Na_2O than the average glaucophane-schist. This is due to the higher proportion of aluminous hornblende and the virtual absence of albite.

(e) Mineralogy of the Amphiboles:

(i) Glaucophane: Lacroix, Murgoci and others regard the atomic ratio of ferric iron to aluminium as being the most important factor in determining the optical properties of the blue amphiboles. In particular, it influences the intensity of the pleochroism, extinction angle, and the position of the optic axial plane. Soda and ferrous iron play little part in determining the optical properties.

In glaucophane the ratio of Fe''': Al is less than unity, while in crossite it approaches unity, becoming increasingly high towards the composition of riebeckite.

The Knockormal blue amphibole agrees with glaucophane in this respect, having a Fe''': Al ratio of approximately 2:7, its optics however are like that of crossite.

Murgoci states that glaucophane with a Fe''':Al ratio

Table 6: Analyses of Glaucophane and Crossite Recalculated to Metal Atoms on the Basis of 24(O, OH):

	1.			2.			3.			4.			5.		
Si	7.476	0.524	8.000	7.625	0.375	8.000	7.674	0.326	8.000	7.443	0.557	8.000	7.439	0.561	8.000
Al	1.596	1.072		1.643	1.268		1.527	1.201		1.357	0.800		0.756	0.195	
Ti	0.136			0.040			-			0.185			-		
Fe'''	0.466			0.467			0.262			0.974			1.114		
Fe''	1.283		5.156	1.148		5.128	1.299		5.186	1.331		4.936	1.066		4.262
Mn	0.045			0.053			-			0.009			-		
Mg	2.154			2.152			2.424			1.637			1.887		
Ca	0.734			0.295			0.511			0.632			0.346		
Na	1.971		2.792	1.879		2.200	1.570		2.187	2.007		2.747	1.991		2.384
K	0.087			0.026			0.106			0.108			0.047		
H	1.762		1.762	1.660		1.660	1.788		1.788	1.155		1.155	-		

1. Glaucophane; Knockormal.
2. Glaucophane; San Pablo, California (Basdale).
3. Glaucophane; Mt. Saleve. (Kunitz).
4. Crossite; Anglesey. (Holgate).
5. Crossite; Berkeley, California (Palache).

of 1:3 may be uniaxial with the optic axial plane parallel to (010). Increase in ferric iron causes the optic axial plane to become perpendicular (010), as in crossite (1904, p.365).

It is concluded therefore that the Knockormal mineral represents a case in which the Fe''': Al ratio has just exceeded 1:3 and the optic axial plane lies perpendicular to (010).

The analyses of glaucophane and crossite in Table 5 are given in terms of metal atoms in Table 6.

A uniaxial glaucophane has been described by Blasdale (1901, p.327) and is given under 2 in Tables 5 and 6. It is very similar both chemically and optically to the Knockormal mineral except for the position of the optic axial plane. M. Levy records a glaucophane with 2Vx = 48° and its optic axial plane perpendicular to (010).

The rather high lime content of the Knockormal mineral is also shared by the "glaucophane-actinolite" of Kunitz (1930, p.246), given under 3 in Tables 5 and 6. Blasdale records another uniaxial glaucophane from California which contains 3.03% lime.

It is probable that the high lime content of the Knockormal mineral is responsible for the position of the optic axial plane. Further, its close relationship to hornblende revealed in thin sections suggests that the lime content represents the hornblende (actinolite) molecule [Ca Mg] in the process of replacement by the glaucophane molecule [Na Al], as proposed by Kunitz. This conclusion is strengthened by the fact that in some cases the glaucophane alters to a pale actinolite (p.47).

The blue amphibole barroisite may also be a member of this group characterised by the presence of lime.

It appears therefore that all those blue amphiboles carrying appreciable lime can be regarded as members intermediate between true non-calcic glaucophane and hornblende and are characterised by very variable, and in some cases abnormal, optics (e.g. barroisite).

Probably many minerals called "glaucophane" are lime-bearing and may form under different conditions from those giving rise to normal glaucophane (p.53 and Holgate, 1951).

(ii) <u>Hornblendes</u>:

A green amphibole occurs in glaucophane-schists from California which in its mode of occurrence and optics resembles that from Knockormal. This mineral is described by Murgoci as karinthine (carinthine) which he regards as a member intermediate between hornblende and glaucophane.

Whether the name carinthine should be retained appears doubtful. The analysis given by Dana (1894, p.395) places it among the common aluminous hornblendes.

The "karinthin" of Kunitz (1930, p.245) is, however, more allied to actinolite having only 3.77% of Al_2O_3.

Hey (1950, p.313) regards carinthine as synonymous with barriosite.

It is concluded therefore that the Knockormal green amphibole is best referred to as a rather sodic, but nevertheless normal, aluminous hornblende, and no special name appears to be justified.

(f) Origin of the Glaucophane - schist Assemblages:

Little direct evidence on the origin of the glaucophane-schists can be obtained in the field due to the poorly exposed nature of the ground. Two main points emerge however:

(i) They are associated with ultrabasics, granulites and altered gabbros.

(ii) Their chemical composition, the presence of saussuritic aggregates and relict textures, suggest derivation from gabbroidal rocks.

It is possible that the glaucophane-schists were derived from gabbros similar to those cropping out nearby although no definite transitions can be observed. An analysis of this gabbro, which has been saussuritized and amphibolized, is given in Table 11, p. 102.

Analyses of the glaucophane-schists and gabbro are plotted, for comparative purposes, on an ACF diagram in Fig. 4.

It is concluded, on the basis of evidence supplied by the granulites (p. 76), that the glaucophane-schists are inclusions in the ultrabasic rocks and represent a pre-ultrabasic group of basic rocks disrupted and metamorphosed by the ultrabasics. Comparisons with other areas in which metamorphic rocks are associated with ultra-basics will be given subsequently (p. 79).

(g) Physical and Chemical Conditions in the Formation of Glaucophane and Glaucophane-Schists:

The presence of glaucophane-schists in association with granulites exhibiting relict igneous textures suggests that high pressure or shearing stress are not necessary in their formation. The precise position of the glaucophane-schist facies in terms of temperature and pressure is, however, a matter of some doubt (cf. Turner, 1948; Schürmann, 1953).

The presence of soda in minerals other than felspar has been regarded as evidence of high pressures (Harker, 1932) while the high density of minerals often associated with glaucophane in many parts of the world (e.g. lawsonite, pumpellyite) is also suggestive of formation under high pressures. None of these minerals are confined to glaucophane-schists however, some have been found as infillings of amygdales and as alteration products of unmetamorphosed rocks. Glaucophane itself is known as a product of alteration in non-metamorphic rocks.

The fact that glaucophane does frequently occur in schistose rocks may only imply that shearing stress and high pressure promote migration and difussion of material, partly aqueous solutions, within the rock, and does not neccessarily mean that glaucophane is a product of stress alone.

A reaction between albite and chlorite has been regarded as the most likely in the formation of "normal", non-calcic glaucophane. Such a reaction is not favoured by a hydrous environment since the process is one of dehydration (e.g. eclogite-glaucophanite facies):

$$Mg_3(OH)_4Si_2O_5 + 2Na\ Al\ Si_3O_8 \rightarrow Na_2Mg_3Al_2(OH)_2Si_8O_{22} + H_2O$$

This reaction does not appear to have taken place in the formation of the Knockormal glaucophane-schists, since glaucophane occurs as rims replacing aluminous hornblende. This mode of formation tends to be confirmed by the alteration of glaucophane to actinolite and albite (p. 47), the glaucophane being notably calcic.

The approximate position of the field for albite-epidote-glaucophane (a common assemblage) is shown in Fig.5, plotted in terms of ACF and Na_2O on a tetrahedral diagram. The actual area occupied by the Knockormal rocks and Washington's average basic glaucophane-schist is shown as a dark area lying on the plane of the albite-epidote-glaucophane field.

Since the Knockormal glaucophane is lime-bearing it does not, strictly speaking, lie exactly on the albite-epidote-glaucophane field, but is displaced towards the field of albite-epidote-actinolite. Between these two fields will lie a series of fields embracing assemblages characterised by albite, epidote and various amphiboles between the limits of actinolite on the one hand and true glaucophane on the other.

Other features brought out by the tetrahedral diagram are:

(i) Alumina and lime should be critical in the formation of the glaucophane assemblage.

(ii) Soda should not be critical but in general high soda does not appear to favour the formation of glaucophane.

(iii) With increasing lime all fields tend to converge.

To determine whether or not chemical composition is a factor in the development of glaucophane-schists, analyses of the Knockormal rocks and Washington's basic glaucophane-schists have been examined to test their correspondence with the features predicted on the tetrahedral diagram:

(i) Alumina is fairly constant in amount ranging from 13% to 19%, the greater bulk averaging 15%. Lime is more variable but where it is high the rock also has high ferric iron suggesting that more epidote is present in the rock.

(ii) Soda is very constant around 3%, none of the rocks being especially sodic.

(iii) An increase of lime up to a certain value will cause the albite-epidote-glaucophane field to converge with that of albite-epidote-actinolite (and the green-schist facies in general) which might explain the frequent association of glaucophane-schists and green-schists.

It is concluded that the formation of basic glaucophane-schists is to some extent dependent on chemical composition, especially the amounts of alumina, lime and soda. Further, it is probable that different equilibrium assemblages exist depending on the lime content of the glaucophane, calcic varieties perhaps forming under conditions of lower pressure (? and temperature) than true glaucophane assemblages.

B. "Eclogite"

(a) Field Relationships:

A knob-like mass of eclogitic rock some 10 feet in diameter is exposed at the north-eastern end of the ridge immediately beside the pyroxenite dyke (Fig.2).

The rock appears to be an erosional relic standing as an isolated block on the summit of the ridge which is here composed of pyroxenite. No contacts are exposed and the obvious interpretation of the block is that it formed an inclusion in the ultrabasic dyke.

(b) Petrology:

The rock has been termed eclogite, by Balsillie (1937, p,30) but the mineralogy is not typical of eclogite (pyrope; omphacite). It is slightly schistose and shows considerable variations in grain size. Dark greenish crystals of amphibole are conspicuous together with pink garnets occurring as streaks and disseminations throughout the rock. This causes its specific gravity to be highly variable from place to place. Values ranging from 3.166

to 3.444 have been obtained.

The rock consists typically of garnet, pyroxene, amphibole, clinozoisite, serpentine and spinel, in approximate order of abundance.

The garnet appears to be dominantly pyrope with N = 1.742 and a specific gravity of 3.670. From Eskola's table (1921, p.18) the composition may approximate to $Fe_{23}Mg_{65}Ca_{12}$. The garnet may include crystals of pyroxene, and amphibole may include the garnet. Perculiar "graphic" intergrowths of amphibole and garnet occur (Plate 20, B).

The pyroxene is quite colourless and tends to be euhedral. A strong parting parallel to (100) is common and may in some cases appear stronger than the (110) cleavages.

The value $2V_z = 56^\circ - 58^\circ$; Z:c = 41° and the birefringence is 0.025. The mineral is probably a diopside (var. diallage) and closely resembles that in the adjacent wehrlite (p. 25).

The amphibole builds large plates and some may be derived from pyroxene, but is is by no means certain that this is always the case.

The pleochroism is very weak with X = colourless, Y = very pale green and Z = very pale blue. The value of $2V_x$ is $90^\circ - 92^\circ$; Z:c = 26° and the birefringence is

0.026. It is probably related to edenite.

Large crystals of clinozoisite occur sporadically in some parts of the rock.

Serpentinous areas have a form suggesting derivation from olivine and are occasionally associated with aggregates of brilliant green ceylonite (Plate 20, A).

In one slide aggregates of a dusty saussuritic material occur within, and generally associated with, the large crystals of clinozoisite.

Since no analyses of the rock of its constituents have been made the term "eclogite" is provisionally retained for convenience.

(c) Alteration:

Like the glaucophane-schists the eclogitic rock has been subjected to later crushing producing local granulation and cataclastic textures. Veins of prehnite are common in the rock.

(d) Genesis of the Garnet:

It is certain that the garnet has been derived from the amphibole, the latter never occurring as kelyphitic borders (cf. Harker, 1950, pp.309-310). The unusual "graphic" intergrowths of the two minerals and the fact that the amphibole is rather euhedral and never reveals a habit suggestive of its derivation from garnet lends support to this view.

The development of garnet from amphibole would involve mainly dehydration and desilication, probably accompanied by loss of lime.

(e) Origin of the Eclogitic Rock and Glaucophane-Schists:

The association of eclogitic rock and glaucophane-schists at Knockormal, suggests, as in other parts of the world, a similar origin for both rocks which occupy opposite ends of the same NE trending ridge. Whether the pyroxenite dyke includes also the glaucophane-schist to the SE can not be definitely ascertained.

Eclogite occurring as inclusions in ultrabasic rocks is a common phenomenon; Murchison, as early as 1845 observed in the Ural Mountains, "... a perculiar garnet rock enveloped in serpentine", (1845, p.435).

A similar origin is ascribed to the Knockormal rock which is regarded as being originally olivine gabbro. Since the rock is not a typical eclogite its formation may take place under conditions of lower temperature and pressure than true eclogite (cf. Dengo, 1950, p.877). Similar assemblages which are typically albite-free have been considered metastable phases equivalent to the amphibolite facies (Dengo, op.cit.).

It is concluded that the eclogitic rock formed part of a pre-ultrabasic group of basic rocks which were disrupted and metamorphosed by the ultrabasics.

Since the eclogite and glaucophane-schists form rocks quite distinct mineralogically from other metamorphic rocks in the area (e.g. granulites) they may represent either (a) rocks originally similar to those from which the granulitic varieties have been derived but having a different metamorphic history or (b) have been derived from a different group of rocks, possible situated at a greater depth than those from which the granulitic rocks are derived.

These points will be considered later following a treatment of the other basic rocks and their metamorphic derivatives (p. 132).

C. Granulitic Rocks.

(a) Distribution and Field Relations:

Hornblende and pyroxene-granulites are developed in association with the serpentinite of the southern belt, being quite absent elsewhere, except for a small development at Knockormal (Plate 1).

In general the rocks form small rounded masses, seldom larger than a few feet in diameter and appear as conspicuous projections above the general level of the adjacent serpentinite.

Contacts with the serpentinite are rarely exposed and the rocks all possess a tough flinty fracture suggesting hornfels.

(b) Granulites: Poundland Type.

(i) Occurrence:

Near the head of the Poundland Burn several boss-like masses of granulite occur. One of these masses is markedly elongate in outcrop, attaining a length of some 150 yds. and a width of little more than 25 feet. This dyke-like mass trends approximately E-W and provides an excellent example in the development of the granulitic rocks from basic intrusives.

(ii) Petrography:

The central part of the exposure is gabbroidal in texture but close inspection reveals that the original intergranular boundaries have been blurred.

In thin sections the most striking feature is the granulation of the primary pyroxene which is colourless and diallagic. Rod-like inclusions of ore are common and often serve to emphasise the cleavage.

Granulation into secondary clear diopsidic pyroxene is in progress around the margins and along the cleavages of the primary pyroxene. That the process is not purely mechanical seems clear from the lack of disturbance in the original crystals and the rock as a whole (Plate 21, A).

During the replacement of the original pyroxene there is a development of secondary ore associated with the secondary pyroxene rendering it almost opaque in some cases (cf. Sutton and Watson, 1951, p.31).

The optical data of the pyroxenes are presented below:

	Primary pyroxene	Secondary pyroxene
Ny	-	1.691
Nz-Nx	0.025	0.028
Z:c	46°	41° - 42.5°
$2V_z$	59°	53°

The composition of the secondary pyroxene approximates to $Ca_{45}Mg_{44}Fe_{11}$ (Hess, 1949, p.634).

The change in the pyroxene seems to be a thermochemical effect involving exosolution and oxidation of the FeO in the original pyroxene producing a strongly diopsidic variety.

Partial amphibolization of both the original and secondary pyroxene is ubiquitous. The amphibole is a strongly pleochroic reddish-brown variety and appears as anhedral patches and streaks along the margins and cleavages of the primary pyroxene giving the whole crystal a brownish tinge. Where it replaces the secondary pyroxene it is more euhedral and may build large plates, often associated with ore. Amphibole also appears to develop from dispersed chloritic material of doubtful origin.

Table 7. Analysis of Amphibole from Granulite at Poundland and Comparable Amphiboles:

	1.		2.			3.	4.
SiO_2	40.26	Si	5.978		8.000	39.20	41.46
TiO_2	3.38	Al	2.219	2.022 / 0.269		4.88	5.70
Al_2O_3	13.09					12.25	14.24
Fe_2O_3	0.49	Ti	0.376			2.97	3.32
FeO	11.77	Fe'''	0.053			10.49	5.70
MnO	0.21	Fe''	1.462		4.965	0.17	0.08
MgO	12.56	Mn	0.026			11.57	13.68
CaO	12.48	Mg	2.779			12.59	11.62
Na_2O	2.18					2.68	2.29
K_2O	0.79	Ca	1.986			0.88	1.72
H_2O +	2.34	Na	0.624		2.758	1.17	0.12
H_2O -	0.16	K	0.148			0.02	-
P_2O_5	0.42	H	2.318		2.318	-	-
	100.13					99.87	100.35
S.G.	3.205					3.230	3.215

	1.	3.	4.
X	Pale yellow/colourless	Pale yellow/brown	Light yellow
Y	Brown	Medium brown	Red-brown
Z	Deep reddish-brown	Dark brown	Dark red-brown
Nx	-	1.681	1.670
Ny	1.668	-	1.692
Nz	-	1.700	1.701
Nz-Nx	0.032	0.019	0.031
Z:c	16°	13°- 15°	8°-10°
2Vx	74°	82°	81°

1. Brown Hornblende, Poundland Burn. Anal. W.H. Herdsman.
2. " " " " Metal atoms to 24(O, OH).
3. Kaersutite, Skaergaard Dyke. Vincent, 1953, p.34.
4. " Boulder Dam. Campbell & Schenk, 1950, p.684.

An analysis of this amphibole, which is the type of amphibole developed in all the granulitic rocks, is present in Table 7 (1) together with its optical properties.

Large olivine crystals, $2V_x = 80^o$, are sporadically developed and have an elongated prismatic habit. These crystals are also granulated and recrystallised along the margins into anhedral granulitic olivine with the same optical properties as the primary individuals. The olivine is generally slightly serpentinized.

The plagioclase in the rock is entirely secondary in nature and has a granular xenomorphic habit. The form of these granular aggregates still preserves a vague ophitic relationship to the other constituents. The composition is $Ab_{48}An_{52}$ and the crystals have suffered some granulation. The plagioclase is cut by a perculiar system of veins which never cut any other mineral in the rock. The vein-mineral is too fine grained for accurate determination. It generally has a scaly habit, is biaxial positive, with apparently straight extinction and the faster ray lies parallel to a micaceous cleavage. In bulk the mineral is pale green and is probably prochlorite.

In other cases the vein-mineral appears to be rather like saussurite. It is possible that, in fact, the vein-like material represents remnants of the earlier plagioclase

(iii) Textural Variations:

Towards the margins with the serpentinite, the texture becomes progressively finer in grain and, even macroscopically, it is evident that hornblende is more abundantly developed. At the same time the rock becomes more tough and hornfelsic than in the central portions of the mass.

At a point 12 ins. from the assumed position of the contact with the serpentinite the rock is porphyritic in hand specimens. The groundmass has entirely recrystallised to a fine even textured aggregate of granular pyroxene, plagioclase ($Ab_{51}An_{49}$) and brown hornblende together with abundant magnetite. The pyroxene and hornblende do not appear to differ from those in the coarser part of the rock (Plate 21, B).

The porphyritic texture is produced by large relics of primary plagioclase which are highly saussuritized, much cracked, and invaded along these cracks by minerals of the groundmass. It is concluded that this portion of the mass represents the fine-grained marginal phase of an original intrusion.

The smaller knob-like masses of granulite cropping out in the vicinity of the dyke-like body vary in texture from gabbroidal to doleritic and are identical to the rocks just described.

(c) Granulites: Littleton Hill Type.

(i) Occurrence and Field Relations:

Numerous small granulitic masses are associated with serpentinite on the southern slopes of Littleton Hill (Plate 1). They were the first granulitic rocks to be described in the district (Teall, 1899, p.479).

Like the Poundland granulites they have clearly been derived from basic rocks though they are rather finer in grain than those at the former locality. All have a tough flinty fracture.

Texturally they can be divided into three groups, although there is no obvious significance in the distribution of the various types, and the exposures present no indications of original fine grained margins towards the serpentinite.

(ii) Petrography:

Non-porphyritic:

The rocks are deep brown in colour and, like the Poundland varieties, have a hornfelsic appearance. In their mineralogical and textural characters the rocks are analogous to those at Poundland but appear to have been originally finer grained, recrystallisation almost completely destroying the original textures except for occasional phenocrysts of turbid plagioclase.

The texture is saccharoidal and is defined by equigranular secondary pyroxene, brown hornblende and rather poikilitic plagioclase ($Ab_{46}An_{54}$). The resemblance of the rock to beerbachite is striking (cf. Teall, 1899, Plate 22, 1; this thesis Plate 21, C, Plate 22, A).

Although little indication of the original texture remains other than relict plagioclase phenocrysts, the rock has probably been a dolerite (cf. Mort, 1909; Tyrrell, 1909).

Porphyritic:

These rocks are perhaps the most striking varieties of granulite and are composed of euhedral phenocrysts of plagioclase set in a fine grained matrix of sparkling brown hornblende.

A strong thermal clouding is developed in the plagioclase phenocrysts (cf. Macgregor, 1931). When determinations are possible the plagioclase has the composition $Ab_{50}An_{50}$. Many of the crystals are sieved with streaks or aggregates of brown hornblende making up the bulk of the groundmass. This feature is characteristic of many basalts. Sometimes a vague flow-banding is exhibited by the plagioclase phenocrysts.

Smaller plagioclase ($Ab_{48}An_{52}$) individuals comprising part of the groundmass have recrystallized yet still retain their original elongated outline. These crystals exhibit a marked flow-banding (Plate 22, B, C).

In addition to abundant brown hornblende a few shards of reddish-brown biotite occur.

Pyroxene does not appear in these rocks although occasional subhedral dusty remnants of primary pyroxene in glomeroporphyritic aggregates are common.

The general characters of this porphyritic variety are strongly suggestive of its being originally a lava (Teall, 1899, p.479 and this thesis p. 73,74).

Schistose:

Isolated outcrops of schistose granulitic rocks are developed on a small scale. The schistosity, which may lie anywhere between NW and NE, is rather poorly developed and in some cases is not obvious except in thin sections.

The mineralogy of the rock is the same as those previously described.

The degree of deformation does not appear to have been high since aggregates of secondary granules of calcic plagioclase still retain the form of the original laths of plagioclase (Plate 23, A).

(d) Other Developments of Granulite:

(i) Knockormal:

Three small masses of granulite occur associated with the ultrabasics at Knockormal (Fig. 2). The rocks are identical with the non-porphyritic varieties described from Littleton Hill (p. 65).

(ii) Poundland:

Near the foot of the dyke-like body of granulite at Poundland (p. 61) is a small exposure of strongly banded, partly schistose, granulite. It may not be precisely in situ and the exposure is no larger than the field it occupies in Plate 4, A.

The rock consists of alternating dark and light bands which are about 4 ins. in width, each sharply separated from the adjacent bands. The rock is quite unlike any of the adjacent granulites, none of which exhibit the banded structure although their mineralogy is similar.

The dark bands (S.G. 3.142) are strongly hornblendic and cannot be distinguished from some of the Littleton Hill rocks. The texture is thoroughly granular and xenoblastic, the constituent minerals being deep brown hornblende, labradorite and diopsidic pyroxene. No recognisable igneous textures remain and the optical properties of the constituents are the same as those in the normal granulites (Plate 23, B).

There is a slight tendency to schistosity, especially, near the margins with the lighter bands, and is revealed by an approximate crystallographic parallelism of the hornblendes. A little plagioclase and diopside are present but are generally subordinate to the hornblende.

The light coloured bands (S.G. 3.000) are markedly schistose defined by discontinuous streaks composed of granules of colourless diopsidic pyroxene, many of which are altered to an almost isotropic chlorite (var. pennine).

Hornblende is only occasionally developed, but labradorite is abundant and strongly granular and is commonly traversed by numerous saussuritic veinlets.

Bartrum (1928, p.898) has described a banded rock occurring as an inclusion in serpentinite which appears to be identical to the Poundland rock.

(e) Flasered Varieties of Granulite: Millenderdale Type.

(i) Occurrence and Field Relations:

Coarse flasered and partially granulitized gabbros are confined to the region of Millenderdale where they form a series of large prominent knolls projecting above the level of the serpentinite (Plate 1 and Plate 4, B). An exposure lying on the south side of a dry-stone dyke running in an easterly direction from Millenderdale farm may be taken as a typical example.

The trend of the flaser-planes varies from N-S in some parts to almost E-W in others.

(ii) Petrography:

The centre of the mass is an exceedingly coarse ophitic gabbro; one of the coarsest in the district

(Plate 24, A). There appears to be no significant difference in the optical properties of the minerals from those described in the dyke-like body at Poundland (p. 61).

Large plates of primary diallagic pyroxene, strongly schillered with ore, are in the process of granulation around their margins with the development of colourless granular secondary pyroxene. Brown hornblende is also developing from both the primary and secondary pyroxene (Plate 24, B).

At this stage there is no recrystallisation of the plagioclase which remains as large, deeply saussuritized crystals, ophitically related to the pyroxene. Occasionally large individuals or aggregates of epidote occur within the plagioclase.

Apatite is always an abundant accessory.

As the margins of the mass are approached deformation becomes increasingly intense, the ophitic texture is quickly destroyed and the rock becomes flasered. A rude foliation may be developed by the "streaking-out" of the plagioclase and, to a lesser extent, the dark glistening PLATES of brown hornblende (Plate 24, C).

Thin sections reveal that, with the advent of shearing, there is an almost immediate and complete replacement of any primary or secondary pyroxene by brown hornblende. The shattered plagioclase, while generally the same deeply saussuritized variety as in the unsheared central portion of the mass, in places develops occasional clear granules of secondary plagioclase, generally andesine.

At the margins of the mass shearing reaches the stage where dense even-grained bands are developed with a granular texture comparable to that in some of the Littleton Hill rocks. These granulitic bands may show sharp or gradational junctions towards the coarser flasered bands (Plate 25, A B).

In the granulitic bands most of the plagioclase has recrystallised into xenomorphic granules which, in association with the brown hornblende, produce a typical beerbachitic texture. Hence, although these granulitic bands are closely associated with coarser bands exhibiting marked deformation, they are not themselves obviously schistose.

(f) Contact Relations with the Serpentinite:

In only one locality (Littleton Hill) was a junction between a granulite of the non-porphyritic type and serpentinite obtained. The contact was laid bare by removal of the top soil.

The serpentinite at the contact is quite decomposed and fragmented but a specimen 9 ins. from the contact is quite undeformed and exhibits no contact effects. Similarly

Table 8: Chemical Analyses of the Granulitic Rocks:

	1.	2.	3.	4.
SiO_2	45.70	43.84	51.03	45.86
TiO_2	2.60	2.32	3.04	0.97
Al_2O_3	13.60	15.35	13.69	16.33
Fe_2O_3	2.32	2.09	2.06	1.49
FeO	9.47	10.66	12.02	7.48
MnO	-	0.21	0.22	0.24
MgO	10.53	8.26	4.55	9.64
CaO	10.08	8.02	7.46	9.42
Na_2O	3.74	4.09	4.23	3.02
K_2O	0.56	1.42	0.50	1.39
H_2O +	1.19	2.63	0.82	3.52
H_2O -	0.01	0.37	0.28	0.33
P_2O_5	0.26	0.58	0.31	0.07
FeS_2	0.08	-	-	-
Cr_2O_3	0.14	-	-	-
	100.28	99.84	100.21	99.76

1. Hornblende granulite, Littleton Hill. Balsillie, 1932, p.122.
2. "Hornblende-schist", " " Beveridge, 1950, p.92.
3. Hornblende granulite, Garnaburn. " ibid., p.103.
4. Pyroxene granulite, " " " p.111.

the granulite at the junction exhibits no change from that at the centre of the mass, which in this case, is some 8 feet wide and 20 feet long.

It is concluded therefore that the development of slightly schistose granulites is not connected with the serpentinite junctions at present exposed.

(g) Later Veining and Alteration of the Granulites:

The development of later veins of prehnite is common in almost all the granulites, together with the saussuritization of the secondary calcic plagioclase.

A vein of serpentinite cuts the banded granulite at Poundland and serpentinizes the rock along its margins (Plate 4, A). Veins of talc occur in the rock in addition to sporadic veins of chrysotile.

Another vein of diopside-zoisite rock cuts the banded granulite (p.108).

(h) Chemical Compositions:

Four analyses of the granulitic rocks are given in Table 8.

There is little unusual in their compositions which agree closely with analyses of unmetamorphosed diabases from Lendalfoot (Table 9). However MgO and TiO_2 tend to be higher. The ratio of MgO:CaO in analyses 1, 2 and 4 is close to unity and Fe_2O_3 is uniformly low.

Possible chemical affinities with other members of the complex will be considered subsequently (p.131).

(i) Genesis of the Granulites.

Non-flasered Varieties of Granulite:

The origin of the granulitic rocks presents one of the most difficult problems in the district and was the object of much study by earlier workers (cf. Teall, 1899; Mort, 1909; Tyrrell, 1909; Balsillie 1932 and 1937; Beveridge, 1950; Bailey, 1952).

Considerable differences of opinion exist between almost all those who have studied these rocks. The conclusions reached by previous workers are summarized below, many however, although putting forward new hypotheses, have not attempted to reconcile them with other aspects of the problem:

Age of the Rocks:

(A). Pre-Arenig (Balsillie)

(B). Ordovician (All other workers)

Nature of Original Rocks:

(A). Lavas (Teall)

(B). Gabbros and dolerites (All other workers)

Relationship to the Ultrabasics:

(A). Intrusive (Mort, Balsillie, Beveridge, Bailey)

(B). Inclusions ((?) Teall, Tyrrell).

Cause of Metamorphism:

(A). Unknown (Balsillie - uncovered granite?)

(B). Peridotite (Teall, Tyrrell)

(C). "Late consolidation effect of gabbros and dolerites - pneumatolytic action" (Beveridge)

(D). Later basic and acid intrusions (Bailey).

Date of Metamorphism:

(A). Pre-Arenig and pre-serpentinization (Balsillie)

(B). Ordovician and pre-serpentinization (Beveridge)

(C). Post-serpentinite (Bailey)

Teall (1899, p.479) regarded the porphyritic granulite at Littleton Hill as a thermally altered "diabase-porphyrite". Hence all the granulitic rocks in the area are shown in the Geological Survey (Sheet 7) Map under the heading of "? contact altered lavas".

All later workers have regarded the rocks as metamorphosed gabbros and dolerites and are agreed that thermal metamorphism is the dominant factor in their development.

If the rocks are regarded as intrusive into the ultrabasics the cause of the thermal metamorphism becomes a difficult problem since in many localities the granulites are associated only with ultrabasics. Furthermore, any thermal metamorphism must antedate serpentinization since no thermal effects are to be seen in the serpentinite. There are, however, no signs in the serpentinite to suggest its having previously undergone thermal metamorphism. Thus if metamorphism antedates the peridotite (or serpentinite) its cause is quite unknown.

In no case is it possible to demonstrate that the rocks from which the granulites are derived were intrusive in the ultrabasics. Balsillie (1937) claimed that at Garnaburn a granulitized dolerite intrudes serpentinite which is quite unaltered.

Beveridge and Bailey, while still supporting an intrusive origin for the granulites, considered the evidence at Garnaburn inconclusive, the former stating that the granulite might well be an inclusion in the serpentinite.

Bailey regards the metamorphism as "post-serpentine" and produced by re-heating of earlier intrusions by later intrusions of gabbro, followed locally by granite, which sometimes re-used channels partially blocked by the earlier intrusive masses.

If this is so the following points must be reconciled:

(i) The lack of metamorphism in the serpentinite.

(ii) No later intrusives are associated with many of the granulites (e.g. Littleton Hill).

(iii) Granites occur only at the northern margin of the area, 3 or 4 miles away from the nearest granulite locality, although a few small veins of albitite are occasionally present.

(iv) Later alteration of the granulites (prehnite veining) is analogous to those effects produced in rocks adjacent to the serpentinites and is regarded as related to serpentinization (p.108).

Tyrrel concluded that the granulites were not intrusive in the ultrabasics but were derived from an earlier series of basic intrusives overwhelmed and metamorphosed by the peridotite, now serpentinite. Local deformation exhibited by slightly schistose granulites he regarded as produced by marginal shearing accompanying the ultrabasic intrusion. A xenolithic origin is also implied by Teall.

It is concluded that Tyrrell's hypothesis provides the only solution to the problem which is consistent with all the observed facts accounting for:

(i) The cause of the thermal metamorphism.

(ii) The constant association of the granulitic rocks with ultrabasic rocks.

(iii) The unaltered nature of the adjacent serpentinite.

(iv) The absence of deformation in the serpentinite adjacent to schistose varieties of granulite.

(v) The variation in trend of the foliation in the schistose granulites.

The petrographic characters of the porphyritic granulite from Littleton Hill (p. 65) are strongly suggestive of the rock being originally a lava, a conclusion reached originally by Teall but apparently abandoned by later workers in view of the more abundant development of granulites clearly derived from gabbros and dolerites.

In view of this strong possibility an intrusive origin for the granulites into the ultrabasics must be rejected. However it does not in any way invalidate Tyrrell's concept but suggests the peridotite was intruded into a group of lavas and associated intrusives.

Flasered Varieties of Granulite:

Teall (1899, p.477), and later Balsillie (1932, p.118) described the conspicuous knolls of flasered and sheared gabbro at Millenderdale. In addition to the bands of fine grained granulite, which are clearly derived from the coarser flasered gabbros (cf. Plate 25, B), they noted that some granulitic bands appeared to cut across the trend of the flasered gabbro and granulite bands.

A careful study of these rocks led the writer to doubt the cutting (or intrusive) relationships of some of the granulitic bands. Sometimes bands of granulite swell out into large bulbous masses and deflect the flaser planes of the adjacent coarse bands but there is no evidence of an intrusive relaionship.

It is concluded from their field and petrographic characters that they have an origin in common with the non-flasered granulites.

(j) Mode of Emplacement of the Peridotite into the Earlier Basic Masses:

Although the granulitic masses are regarded as inclusions in the ultrabasics it is not suggested that the former have been transported from great depths. It is probable that the peridotite was intruded into the basal members of a thick pile of Arenig lavas and intrusives thermally metamorphosing them and converting them to granulite (cf. Walton, 1951). This origin is based on the chemical affinities existing between the granulites and unmetamorphosed members of the Arenig igneous series (p. 132).

The ultrabasic magma may have re-used the same fissures as those occupied by the earlier basic masses, a conclusion based on the occurrence of dyke-like masses of granulite in the serpentinite. A similar interpretation has been given by Ransome for precisely analogous inclusions of basic rocks (including "dykes") in serpentinite from California (1894, pp.226-231).

Serpentinization of the peridotite followed, the semi-plastic mass being squeezed upward, still with its metamorphosed inclusions, forming "cold" intrusions with stratigraphically higher members of the Arenig volcanic series.

3. Affinities of the Older Basic Rocks with those in Other Areas:

A considerable amount of evidence exists in other areas throughout the world in support of the hypothesis that the glaucophane-schists, eclogite and granulite are inclusions in the ultrabasics (cf. Schürmann, 1953, pp.328-323).

In particular it is considered that the observations of Rutten (1936), Thiadens (1937) and Vermunt (1937) on Cuba can be applied to the Girvan-Ballantrae district.

In Cuba large masses of serpentinite invade a series of Lower and Middle Cretaceous geosynclinal sedimentary and volcanic rocks including radiolarian cherts, Aptychi limestone, spilites, tuffs and diabases. The ultrabasic intrusion accompanied orogenesis and was followed by the intrusion of gabbroidal dykes and masses of diorite rock (hooibergite), pyroxenite and amphibolite (Thiadens, op.cit.)

The margins of the serpentinite at present exposed are entirely tectonic.

Inclusions in the serpentinite are widespread and consist mainly of <u>unmetamorphosed</u> volcanic and intrusive rocks representing the Lower Cretaceous igneous series. In addition highly metamorphosed rocks occur of which the following list is typical (Rutten, 1936, pp.15-18):

(1) Albite-epidote-schist
(2) Chlorite-schist
(3) Actinolite-schist
(4) Quartz-albite-glaucophane- schist.
(5) Muscovite-schist
(6) Amphibolites (±glaucopha
(7) Glaucophane-eclogite
(8) Eclogite.

Many of the above rocks form parts of an older, pre-ultrabasic series of schists which crop out elsewhere on the island, others may be metamorphosed Cretaceous volcanics.

From such an assemblage of metamorphosed and unmetamorphosed inclusions it must be supposed that the final intrusive phase of the serpentinite was a "cold" one, and probably largely tectonic, while an earlier peridotitic phase metamorphosed and disrupted some of the basic rocks at depth.

Similar relationships appear to exist throughout the Caribbean, while inclusions in serpentinite are known from such areas as New Zealand and Rumania.

4. <u>Younger Basic Rocks</u>.

(a) <u>Distribution and Field Relations</u>:

A varied series of basic rocks intrudes the ultrabasics, and less commonly, the lavas (Plate 1). The largest basic intrusion in the area is that which makes up Grey Hill and Byne Hill and is continuously exposed for a distance of over 2 miles.

With the exception of exposures at Byne Hill and on the shore at Lendalfoot, the relationships existing between the basic and ultrabasic rocks are not very well exposed.

The basic rocks can be divided into two main petrographic types, diabases[x] and gabbros.

(b) Diabases: Lendalfoot Type.

(i) Field Relations and Form:

Cropping out on the shore just to the north of Lendalfoot are a series of narrow elongated masses of diabase which rise up above the general level of the serpentinite (Fig. 6). The masses vary in length up to 100 yards and are some 25-30 feet wide, rising to a height of 20 feet. They are probably dykes intrusive into the surrounding ultrabasics (Plate 5, A).

Smaller and more obviously dyke-like bodies traverse the ultrabasics (Plate 5, B, C).

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x The term "diabase" is used throughout this thesis and is applied to those intrusive rocks which are highly altered and possess doleritic textures.

Identical rocks belonging to this group occur inland at Cairn Hill, Byne Hill and scattered throughout the southern belt of ultrabasics, particularly in the region of Knockdolian. Many of these masses have the form of small bosses but are always poorly exposed.

(ii) Petrography:

A conspicuous mass of diabase cropping out on the shore at the north-easterly end of Fig.6 (Plate 5, A) will be taken as a typical example.

The central portion of the mass is a greyish medium grained rock, the texture being generally rather granular but occasionally slightly ophitic.

Int hin section the rock is highly altered except for anhedral, ragged crystals, of a pink titaniferous augite with $2V_z = 48^o$; $Z:c = 45^o$ and a birefringence of 0.024.

Rather equant idiomorphic crystals of plagioclase are highly altered to a dense sub-isotrophic mass of saussurite and highly birefringent fibrous aggregates of prehnite. Where the rock is more ophitic the plagioclase tends to assume a more lath-like form (Plate 26, A, B).

Chloritic or serpentinous material, magnetite and abundant skeletal ilmenite altering to leucoxene are present in the groundmass.

A feature perculiar to the Lendalfoot rocks is a strong development of veins of calcite, prehnite and pectolite. The veins tend to be sub-parallel and at any given place are normal to the margins of the mass.

(iii) Contact Phenomena:

Original Textural Variations:

Towards junctions with the serpentinite all the masses of diabase become finer in grain and increasingly porphyritic.

The plagioclase occurs in the form of large euhedral phenocrysts imparting the porphyritic texture to the rock and as small laths, often with a vague flow banding (Plate 27, A). The altered plagioclase is colourless except for some areas of semi-opaque saussuritic material. Between crossed nicols the phenocrysts are almost completely isotropic except for a few tiny granules of quartz and (?)albite. The isotropic material constituting the remainder of the crystals is too fine grained for precise determination but is probably zoisite.

Euhedral crystals of pyroxene are less altered although they are often rendered turbid-looking due to the development of a fine dusting of ore, common in the pyroxene of the ultrabasics. When fresh the pyroxene is colourless and with a highly variable axial angle. Two determinations were possible; one gave $2V_Z$ = 56° and the other 64°. No further optical properties could be obtained because of the lack of suitable sections. The pyroxene is probably more diopsidic than that in the coarser central part of the mass.

The ground mass is almost indeterminable but consists mainly of isotropic laths and granules of altered plagioclase together with granular pyroxene, variously altered. Minute grains of epidote, ore, quartz and (?)albite lie in an isotropic base of what was probably glassy material of felspathic composition.

It is concluded that the textural variations of the diabase towards its margins are indicative of chilling against the adjacent ultrabasic rocks (cf. Peach and Horne, op.cit., p.450; Tyrrell 1933, p.76).

Changes Associated with Serpentinization:

At the contacts with the serpentinite, most of which are vertical or nearly so, the diabase assumes a perculiar glazed porcellanous appearance and is extremely tough with a sharp flinty fracture. Bonney (1878, p.775) regarded this as produced by contact metamorphism of the diabase by the later ultrabasic rocks.

Some contacts are marked by shearing and other signs of deformation of the serpentinite, which often sends obviously sheared apophyses showing mechanical intrusions into the diabase. These observations appear to have contributed to Bonney's conclusion that the ultrabasic rocks were later.

Very generally, however, the marginal serpentinite is undeformed and small scale replacement of the adjacent chilled diabase occurs in the form of chloritization and serpentinization, with the development of veinlets and fingers of serpentine (Plate 6, A).

The prominent veins of calcite, pectolite and prehnite traversing the diabase suggest, by their direction, that they occupy tension cracks produced during the cooling of the rock.

Balsillie (1932, p.124) noted that the veins, some of which are 2" wide, can not be observed to cut the serpentinite, stating, "Such an observation might easily lead one to infer some sort of xenolithic relation for the diabase masses".

The abrupt termination of these veins at serpentinite contacts is understandable however, since the serpentinite has been affected by movement posterior to the intrusion of the diabases.

Evidence will be presented subsequently demonstrating a close relationship between the development of lime silicate veins and the process of serpentinization (p. 108). Lime-silicate veins traversing serpentinite in other localities will also be described (pp. 107-108).

Alteration of the Serpentinite:

Other than being affected by post-serpentinite deformation, the serpentinite associated with the diabases exhibits no indications of thermal metamorphism.

Adhering to the diabase in some declivities on the southern side of the large north-easterly mass (Fig. 6) is a compact serpentinite which is tougher than that along the majority of the contacts and elsewhere on the shore.

In thin sections the typical serpentinite mesh-structure is lacking, the rock consisting of closely sutured grains of a greyish substance resembling serpophite but giving a uniaxial negative interference figure and apparently secondary after olivine. Each grain is packed with tiny grains of ore.

This phenomenon, while resembling the initial stages of serpentinization (p. 22) differs in the absence of fresh olivine kernals which occur at this stage of serpentinisation.

Table 9: Analyses of Lendalfoot Type Diabases:

	1.	2.
SiO_2	47.50	46.47
TiO_2	4.49	3.69
Al_2O_3	12.39	12.87
Fe_2O_3	4.17	2.40
FeO	10.60	11.68
MgO	4.27	5.48
CaO	7.37	9.87
Na_2O	4.88	4.00
K_2O	0.89	0.68
H_2O +	2.62	2.56
H_2O -	0.20	0.06
P_2O_5	0.78	0.50
Cr_2O_3	-	0.02
FeS_2	0.02	0.09
	100.18	100.48

1. "Albite Diabase", Lendalfoot, Balsillie, 1932, p.126.
2. " " " " " "

Crystals of bastite are present, some of which have been converted to tiny fibres of pale green amphibole. Occasional grains of fresh bronzite remain and veins of cross-fibre chrysotile traverse the rock (Plate 27, B).

It is concluded that prior to serpentinization the ultrabasic rock formed a contact altered selvage against the intrusive diabase. The actual nature of its metamorphism is obscure but the unusual texture suggests a form of annealing. The ore associated with the altered olivine may be the result, not of serpentinization, but of exosolution and oxidation of iron during thermal metamorphism.

(c) Analyses:

No new analyses of the diabases have been made. Two earlier analyses are quoted in Table 9. The rocks greatly resemble the analyses of the granulites (Table 8). All have rather high TiO_2 and Na_2O, the former being represented largely by the titaniferous pyroxene.

(d) Gabbros.

Byne Hill Type:

(i) Distribution and Field Relations:

Gabbros of this type form the Grey and Byne Hills and constitute the largest basic intrusion in the district. The gabbro occupying the southern slopes of Byne Hill may be taken as typical of the whole mass.

The gabbro is associated with serpentinite the junctions with which are generally lines of movement (Plate 2). Intrusive into the gabbro is a mass of granite forming the summits of Grey and Byne Hills (p. 122).

(ii) Petrography:

The gabbro is extremely variable in texture being in parts coarse, almost pegmatitic, and in other doleritic. In the coarse-grained phases plagioclase or dark minerals may severally form irregular concentrations. Planar or layered structures, however, are never developed (Plate 28, A).

The rocks consist of altered plagioclase in a strongly ophitic relationship to pyroxene, generally amphibolized. Olivine is sparingly present and apatite and magnetite are common accessories.

Plagioclase ($Ab_{56}An_{44}$), in various stages of alteration to saussurite and secondary sodic plagioclase ($Ab_{82}An_{18}$) forms large idiomorphic crystals, sometimes faintly zoned.

The pyroxene is only preserved as occasional relics: $2V_z = 52^\circ$; $Z:c = 40^\circ$ and a birefringence of 0.025. Insufficient quantities of the mineral remain for the determination of its refractive index. It is probably a diopsidic variety however.

Table 10: Modal Analyses of the Byne Hill Gabbro:

Vol.%	1.	2.
Pyroxene	2	Nil
Brown Hornblende	26	3
Green "	16	33
Saussurite	29	21
Secondary plagioclase	20	32
Chlorite	6	5
Olivine, Apatite, Ore	11	6

The replacing brown hornblende is strongly pleochroic (X = colourless, Y = pale brown, and Z = deep brown); $2V_x$ = 80° - 82°; Z:c = 18°; birefringence 0.025 and Ny = 1.686. In most specimens the brown hornblende grades marginally into a blue-green variety, the latter often bring optically continuous with the brown as judged by the positions of extinction.

The blue-green hornblende has the pleochroism X = colourless, Y = grass green and Z = blue-green; $2V_x$ = 75°; Z:c = 17°; birefringence 0.022 and Ny = 1.658.

A single fresh grain of olivine proved to be rather fayalitic ($2V_x$ = 68°).

Secondary magnetite is closely associated with hornblende, often as cores within the crystals. Apatite is sparingly present together with a little chlorite after amphibole (Plate 28, B).

The blue-green amphibole increases in amount simultaneously with increase in the amount of sodic plagioclase, so that eventually the brown variety is quite subordinate, the blue-green variety occurring as independent fibrous clusters. This relationship is illustrated by the accompanying modal analyses (Table 10).

It is concluded that lime liberated from primary plagioclase during its conversion to a more sodic variety is absorbed during the development of the blue-green hornblende from the brown variety.

(iii) Contact Phenomena

Original Textural Variations:

An almost vertical contact between gabbro and serpentinite is excellently exposed on the south-eastern slopes of Byne Hill. Unlike the other contacts in the immediate vicinity this junction has not suffered post-serpentinite deformation (Plate 7, A, B).

Just as in the Lendalfoot occurrences the gabbro shows progressive fine graining towards the contact and similarly develops a glazed porcellanous appearance and becomes extremely tough, with a sharp flinty fracture.

This obvious development of a chilled margin towards the ultrabasic rock was observed by Tyrrell (1933, p.71) who applied the name "pseudophite" to the flinty margin. However, this name has been applied to a variety of serpentine with a hardness of 2.5 (Dana, 1894, p.652) and is hardly applicable to the Byne Hill rock.

Changes Associated with Serpentinization:

Thin sections cut across the contacts between the gabbro and serpentinite are shown in Plate 29, A, B, C, Plate 30, A. Progressing inwards from the serpentinite into the gabbro four distinct zones of alteration can be recognised:

(1) The serpentinite at the contact is a normal serpentinized harzburgite with accessory picotite. The mesh-structure is still preserved although on a finer scale than is usual. In some cases there is a suggestion of flowage in the serpentinite (cf. p. 19). Tiny granules of unaltered olivine are occasionally present.

(2) The contact between the serpentinite and the chilled margin of the gabbro is to some extent gradational over a short distance, the marginal gabbro being itself serpentinized. This zone is characterized by the development of rather fibrous opaque ore and there is no evidence of cataclasis.

Felspar microlites $\frac{1}{2}$ m.m. in length occur, their outlines being only visible in ordinary light. Viewed between crossed nicols the crystals merge into the fine grained groundmass being composed of the same almost isotropic zoisitic material.

Rather corroded but strongly euhedral crystals of pyroxene are all converted into pennine with associated fine grained ore. Often an hour-glass structure in the original pyroxene is preserved by varying density of the granules of secondary ore.

The groundmass, which appears to have been composed largely of fine-grained felspar and pyroxene, possibly with some glassy material, is altered to a dense mass of sub-isotropic zoisite and granular ore.

(3) A change in the form of the opaque ore occurs in this zone. It loses its fibrous habit and assumes the form of evenly distributed rounded granules. More felspar laths and pyroxene are developed, but otherwise the mineralogy is identical with that in the previous zone.

(4) There is a significant change in mineralogy along a sharp line of junction which is highly irregular and, although approximately parallel to, is not coincident with, the actual serpentinite contact. Laths of felspar are altered to zoisite and subordinate (?)prehnite. In some cases the felspar exhibits marked flow banding which does not follow the details of the boundary of this zone, but is parallel to the more regular serpentinite contact (Plate 29, A).

Pyroxene is no longer pseudomorphed by pennine and ore but is quite fresh and euhedral with frequent hour-glass structure. This structure is generally defined by a pink coloration, presumably due to the presence of titania. In other cases the coloration is produced by sectors of deep reddish-brown amphibole (p.93). A concentric zoning is frequently also present.

The unaltered pyroxene is quite colourless: $2V_z = 50^o$; $Z:c = 39^o$ and a birefringence of 0.026.

The groundmass is lighter in colour due to the almost complete absence of ore and is composed of a dense cloudy saussurite. Under high power it can be resolved into a feathery aggregate in which can be observed tiny granules of epidote, together with some pyroxene. Tiny fibres of tremolite also contribute to the groundmass.

Veins of cross-fibre chrysotile sometimes cut across the various zones (Plate 29, C). Where they occur in zones 1, 2 and 3 they are composed of chrysotile. Immediately upon entering zone 4 however they change to aggregates of tiny strongly birefringent fibres arranged normal to the walls of the veins.

The optic axial angle of the mineral is + 54^o; $Z:c$ (?)= 42^o and birefringence 0.035. It is quite colourless and sometimes has a stellate form resembling prehnite. Veins of the same mineral occur in the serpentinite together with zoisite and grossularite (p.108). The mineral is probably a lime-silicate (?)pectolite, but the crystals are too small for precise determination.

The contact rocks are sporadically amphibolized. Pyroxene phenochrysts are often completely pseudomorphed by brown amphibole which may also invest the groundmass. The amphibole is very similar in its optical properties to that in the granulitic rocks.

Zone 4 grades into a normal dolerite about 9 ins. from the contact and thence into gabbro. The doleritic phase might be termed the "zone of prehnite". This mineral is abundantly developed in the form of pseudomorphs after plagioclase and as replacement veins, often over an inch wide.

These veins appear to be analogous to those developed in the Lendalfoot diabases (p.83).

Two contacts between serpentinite and a porphyritic diabase are exposed in the Byne Hill Burn below Balaclava Wood (Plate 2). The rock is very similar to the Lendalfoot diabases and is probably a dyke.

The diabase is moderately ophitic although there is a tendency towards a more granular texture. Altered plagioclase is abundant and is more euhedral than the colourless pyroxene. Larger plagioclase phenochrysts impart a porphyritic texture to the rock in hand specimen. Skeletal ilmenite passing to leucoxene is generally abundant.

Approaching the serpentinite junction the rock becomes finer in grain and shows the rapid alteration of plagioclase to zoisite. The pyroxene develops the perculiar dusty appearance noted previously (p. 26).

Epidote is developed in the form of large crystals or in clusters, but its precise origin is uncertain.

About 1½ m.m. from the contact the rock assumes a yellow colouration which does not appear to be produced by any significant change in mineralogy, being rather a kind of bleaching. Veins of chrysotile branch into the rock from the serpentinite and produce the same yellow bleaching of the diabase along a narrow zone parallel to the margins of the veins, like that at the actual contact.

Although the serpentinite is sheared at the contact due to post-serpentinite movement no cataclasis can be seen in the diabase. It is concluded that in many cases the serpentinite has acted as a "slide expedient" (cf. Vermunt, 1937, p.17).

(e) Age of the Diabases and Gabbros:

The diabases and gabbros are regarded as intrusive into the ultrabasic rocks prior to their serpentinization. This conclusion is based on the following evidence:

(i) Both the diabase and gabbro exhibit chilled margins towards the serpentinite.

(ii) A selvage of serpentinized harzburgite marginal to a diabase dyke at Lendalfoot appears to have suffered thermal metamorphism prior to its serpentinization.

(iii) There is no sign of alteration of the serpentinite marginal to the diabase and gabbro.

(f) Significance in Relation to Serpentinization of the Ultrabasics:

It has been demonstrated that, although the diabase and gabbro are clearly intrusive in the ultrabasics, they are intruded by the serpentinite and partially serpentinized along their margins. This serpentinization of the later basic rocks is analogous to that occurring in the lavas at Pinbain (p. 29).

Two types of contact are therefore exhibited by basic rocks marginal to the serpentinite, a feature displayed best by the Byne Hill gabbro-serpentinite contact:

(i) A contact representing the original intrusive contact between the basic rock and unserpentinized ultrabasic. This contact is rather regular in form and is the one to which any flow-banding in the basic rock lies parallel. It should be noted that strictly speaking this contact marks only the margin of the basic rock since there is evidence indicating that, in most cases, the serpentinite has been capable of considerable flow-movement during its serpentinization. Hence the serpentinite now in contact with the basic rock is not necessarily the serpentinized representative of the peridotitic rock originally present at the contact.

(ii) A secondary contact is developed by the serpentinization of the marginal basic rock concomitant with the serpentinization of the ultrabasics. The margin of this serpentinized zone towards the unaltered basic rock is highly crenulate, cutting across any structures in the basic rock (e.g. flow-banding).

It is concluded that the contact effects were produced by hydrothermal processes accompanying serpentinization which, in addition to serpentinizing the basic rocks, introduced water, CO_2 and probably lime, forming minerals like prehnite, pectolite, amphibole and grossularite (p. 108).

The presence of chrysotile veins cutting across the earlier contacts suggests that serpentinous solutions were still active posterior to the general completion of serpentinization.

(g) Thermal Affects at Ultrabasic Contacts:

Bailey (op.cit., p.31) regards the evidence supplied by the contact at Byne Hill as indicative of "reheating by continuance of intrusion", observing that, "this chilled edge has suffered striking thermal metamorphism without any attendant deformation".

It is not clear however whether the toughness of the marginal gabbro is attributable to fineness in grain or hornfelsing. Bonney (op.cit., p.775) regarded the flinty margins of the Lendalfoot diabases as thermally altered by the invading ultrabasics.

It is probable that some thermal metamorphism has taken place (e.g. amphibolization at Byne Hill), but the source of the heat is difficult to ascertain. There is no evidence of the later intrusion of rocks along the junctions as suggested by Bailey.

Becker (1888, pp.119-120) indicated the possibility of heat being liberated during serpentinization. In any mixture of substances capable of reacting upon one another the resulting compounds will be those whose formation is accompanied by the most rapid evolution of heat in adjustment to falling temperature. Since serpentine is the "end-product" of the alteration of many ferro-magnesian silicates it is presumably the most stable phase at normal temperatures and pressures. Its formation will therefore be exothermic in character.

It is possible that heat from such a source might, in a large body of ultrabasic rocks, produce some degree of thermal metamorphism of the contact rocks.

(h) Other Minor Developments of Gabbroic Rocks:

(i) Pegmatitic Diallage-Gabbro; Pinbain:

Intrusive into serpentinite and diallagite on the shore south of Pinbain is an exceptionally coarse, pegmatitic gabbro described earlier by Bonney (1878) and Heddle (1878). The mass appears to include large rounded blocks of serpentinite (Plate 8, A), and is probably a dyke.

In hand specimens large milky white plates of saussuritized felspar are ophitically enclosed by dark brown hornblende in which occasional greenish crystals of original diallage can be seen. The hornblendes may be an inch or more long and appear to retain the fibrous cleavage of the pseudomorphed diallage. Much of the hornblende has been altered to a soft, greasy, iron-stained talc.

The southern margin is not very well exposed but it appears to be an original junction since in places coarse gabbroidal apophyses ramify through the serpentinite and diallagite (Plate 8, B).

The northern margin is a plane of movement truncating the gabbro against serpentinite to the north. This margin has suffered cataclasis; the brown hornblende in the brecciated rock giving it an appearance superficially similar to some of the granulitic rocks.

Whether this mass of gabbro antedates or postdates serpentinization cannot be definitely established.

(ii) Olivine - Enstatite - gabbro; Burnfoot:

Dykes of gabbro varying in width from 10 ins. to ½ inch traverse serpentinite on the shore at Burnfoot (Plate 9, A). Post serpentinite deformation has broken up the dykes, fragments of which occur in the deformed serpentinite (p. 28).

The felspars in the gabbro are replaced by a dense matte of zoisite showing anomalous blue tints, while the enstatite has been partially chloritized. Serpentinous pseudomorphs after olivine are also present (Plate 31, A).

Thin sections have been prepared to show the relation between a small vein of gabbro and the adjacent serpentinite.

Near the contact with the vein the serpentinite becomes richer in iron until at the contact it is rendered nearly opaque. The normally colourless serpophite cores become olive-green and doubly refracting, the mineral being similar to chlorite.

Harker (1904, p.80) referred to the development of a yellow colouration in serpentinite which he regarded as produced by the resorption of secondary ore due to the effects of contact metamorphism of the serpentinite.

It is possible therefore that the gabbroic dykes at Burnfoot are later than the serpentinization of the ultrabasics.

(iii) Ophitic Gabbro: Troax:

Intrusive into lavas and the adjacent ultrabasics at Troax is a series of poorly exposed gabbros which, in contrast to all the other gabbros, are even-grained and uniformly melanocratic (Plate 31, B).

The plagioclase has been altered to a dense saussurite and still retains its ophitic relationship to the ferromagnesian constituents. The pyroxene is pseudomorphed by brown and green hornblende, the green variety often occurring as rims about the brown. Unaltered cores of a colourless pyroxene are occasionally preserved.

The age of these rocks in relation to serpentinization cannot be ascertained.

(iv) Altered Gabbros; Knockormal:

Bosses of a coarse altered gabbro, seldom larger than 10 feet project above the serpentinite at Knockormal (Fig. 2) in association with granulitic rocks and glaucophane-schists. One mass to the NW is rather larger and lenticular in outcrop. No contacts are exposed.

The disposition of these small masses of gabbro might suggest their being simply glacial erratics. However it is difficult to imagine why they are confined to the small area occupied by the serpentinite.

The rocks are strongly brecciated and in places a

Table 11: Altered Gabbro; Knockormal.

	1.	2.
SiO_2	58.16	47.19
TiO_2	0.16	2.09
Al_2O_3	12.82	13.96
Fe_2O_3	1.07	3.39
FeO	5.33	9.01
MnO	0.15	0.47
MgO	8.77	7.10
CaO	6.30	8.08
Na_2O	4.98	4.50
K_2O	0.27	0.70
H_2O +	1.93	2.56
H_2O -	0.14	0.12
CO_2	Nil	0.79
P_2O_5	0.04	0.56
	100.12	100.62
S.G.	2.950	-

1. Altered gabbro, Knockormal. (Anal. W.H. Herdsman)
2. Minverite (albite-gabbro), Cornwall. Dewey, 1910, p.46.

rude schistosity may develop. There is however no indication of thermal metamorphism.

Considerable amounts of prehnite are present in the rocks, often to the exclusion of most of the other minerals ("prehnite-rock").

In its least altered phase the rock is a coarse gabbro with completely altered plagioclase in an ophitic relationship with secondary hornblende containing occasional unaltered cores of pyroxene (Plate 32, A).

The hornblende is a green variety with X = pale green, Y = light olive-green and Z = light blue-green; $2V_x = 78^\circ - 90^\circ$ and Z:c = 23°.

Relics of olivine are occasionally present; while prehnite, pseudomorphing plagioclase or as veins, is always abundant.

An analysis of this rock is given in Table 11, 1.

The precise origin of these rocks is obscure since they never show chilled margins towards the ultrabasics, are considerably altered and appear to be purely fragmental. Their association with metamorphosed rocks regarded as inclusions in the ultrabasics suggests that they may also be inclusions.

(Y) <u>Tertiary Dykes</u>:

Porphyritic dolerite dykes intrude all members of the igneous complex. On the basis of their general NW trend and freshness they are regarded as being Tertiary in age.

One of these dykes on the southern slopes of Byne Hill carries a rather flinty selvage of serpentinite caked onto its side (Plate 2). Thin sections of the altered serpentinite reveal that the original mesh-structure has been almost obliterated and the iron ore dispersed irregularly throughout the slide. A little antigorite is occasionallly seen while picotite is generally present and quite unaltered (Plate 32, B).

Dark ovoid areas can be seen in the slide composed of dense iron ore and a fibrous matte of chlorite. The optic axial angle of the mineral ($2V_x$) is very small or zero. It has straight extinction (or nearly so) and the birefringence is 0.021. There is faint pleochroism from a pale golden yellow to pale green. The lower index of refraction lies just above that of balsam.

The mineral is probably a magnesian-rich chlorite related to amesite, while its radiate habit suggests derivation from anthophyllite or cummingtonite. The distribution of these chloritized bodies is similar to the disposition of bastite or bronzite in the unmetamorphosed serpentinite.

The presence of thermal alteration of the serpentinite adjacent to a basic dyke younger than the serpentinite is further evidence in support of the older masses, producing no contact alteration of the serpentinite, being intruded anterior to serpentinization.

5. Garnetized Gabbros (Rodingites).

(a) Field Relations:

Altered gabbros bearing grossularite are developed in two localities on the southern slopes of Byne Hill (Plate 2):

(i) Three masses are exposed on the slopes of the hill above Balaclava Wood. Their precise form is not very well revealed but they appear to be dykes intrusive into the surrounding ultrabasics which are all serpentinized.

Contacts are exposed in two places, one of which is rather sheared. The other contact is unmoved and the marginal altered gabbro includes small fragments of serpentinite.

(ii) A small exposure of garnetized dolerite occurs further to the west, beside the serpentinite-gabbro contact. This rock is obviously a dyke and may be an apophysis from the main mass of the Byne Hill gabbro.

(b) Petrography:

(i) The rocks are conspicuous in the field being almost pure white and are exceedingly tough with a sharp flinty fracture. Dispersed aggregates or clots of magnetite appear to be the only dark minerals present.

While the bulk of the rock appears to be a dense white saussurite, irregular greyish areas can be seen which are much softer.

A characteristic feature of the rock is its high density (3.24), a value that one would not associate with such a light coloured rock.

Under the microscope the rocks retain an original ophitic texture but the plagioclase has been completely pseudomorphed by minutely granular grossularite with subordinate zoisite (Plate 33, A, B). Only under high power is it possible to resolve the garnet, the average size of which is 0.01 m.m. The combined effect of the minute garnet granules is to render each plagioclase pseudomorph isotropic.

The original ferromagnesian constituent has been converted to a chlorite, generally pennine. Occasional relics of close cleavage planes suggest that the original mineral may have been a diallagic pyroxene.

Prehnite is generally present together with vague saussuritic patches.

(ii) The smaller dyke has a porphyritic texture and is more doleritic. Rather euhedral pyroxene crystals lie

Table 12: Analyses of Garnetized Gabbros (Rodingites):

	1.	2.	3.	4.
SiO_2	38.04	33.95	33.42	40.98
TiO_2	0.82	0.42	0.30	1.01
Al_2O_3	15.07	19.91	14.34	12.77
Fe_2O_3	1.78	1.28	10.32	1.10
FeO	3.02	6.98	2.44	4.06
MnO	0.21	0.28	0.75	0.16
MgO	9.62	5.23	4.66	7.31
CaO	25.84	26.95	29.40	29.40
Na_2O	0.18	0.15	0.14	NIL
K_2O	0.04			0.03
H_2O +	4.19	4.85^x	3.63^x	2.68
H_2O -	1.15			0.31
CO_2	Nil	Nil	Nil	0.07
P_2O_5	0.24	-	-	0.08
	100.20	100.00	99.40	99.96

^{x} Loss on Ignition

S.G.	3.24	-	-	3.33

1. Rodingite, Byne Hill (Anal. W.H. Herdsman).
2. " New Zealand. Marshall, 1911, p.33.
3. " " " " " "
4. " Eulaminna, W. Australia. Miles, 1950, p.125.

in a groundmass composed largely of epidote and zoisite. The garnet is confined largely to irregular branching veins and is associated with zoisite (Plate 33, C).

The vein-like habit of the garnet in this rock is like that occurring at the serpentinite-gabbro contact (p. 93).

(c) Analyses:

An analysis of one of the garnetized gabbros from Byne Hill is presented in Table 12, 1.

The most significant feature is the high percentage of CaO and the low value for silica.

The correspondence of the Byne Hill rock with those garnetized gabbros known as "rodingite" is evident (Table 12, 2, 3 and 4).

(d) Nature of the Garnet:

Attempts to separate the garnet from the Byne Hill rock in quantities sufficient and pure enough for chemical analysis failed owing to the constant admixture of zoisite which appeared to have a rather wide range of specific gravity.

Density determinations made on the garnet using heavy liquid (Clerici Solution) showed a range of 3.491 to 3.398. Refractive index measurements gave values of 1.742 for S.G. 3.491 and 1.718 for S.G. 3.402.

Garnet with the higher values of density and refractive index appears to be normal grossularite (lime-garnet). That with the lower values of density and refractive index may be a hydro-garnet belonging to the series plazolite-hibschite.

Hutton (1943) in a study of the New Zealand rodingites concluded that the garnet was a member of the above series, containing 4.65% of water and named it "hydrogrossular". The mineral differs from normal grossularite in possessing a lower refractive index and specific gravity. The following range is typical: N = 1.6780-1.7243 and S.G. = 3.39-3.46 (Hutton, op.cit.).

It is inferred that the garnet from the Byne Hill rodingite shows a corresponding range in chemical composition and the garnet having lower values of density and refractive index may be hydrogrossular.

(e) Comparable Rocks from Other Areas:

Analyses and petrographic descriptions of rodingites from New Zealand and W. Australia agree exactly with those from Byne Hill (cf. Hochstetter, 1864; Davis, 1871; Marshall, 1911; Grange, 1927 and Miles, 1950).

Furthermore, the rocks are generally in the form of dykes and are always associated with serpentinite.

6. Associated Lime-Silicate Veins:

Reference has already been made to the frequent occurrence of prehnite, pectolite, epidote and other lime-silicates in rocks marginal to the ultrabasics. Small veins carrying zoisite and grossularite occur also in the serpentinite at Byne Hill (p.93).

Similar veins of lime-silicates, often 2 inches wide, traverse the serpentinite at Poundland (Plate 10, A). Another vein cuts the banded granulitic inclusion at the same locality (p.72).

The veins, which are generally milky-white and moderately tough, are composed of a dense mass of zoisite, often with patches of minutely granular garnet. In addition small granules of epidote occur together with granular (?) diopside. The veins show no signs of being derived from igneous rocks.

7. Origin of the Rodingites and Lime-Silicate Veins:

The evidence indicates clearly an intimate relationship between serpentinite and lime-metasomatism in the marginal rocks, together with lime-silicate veins. In addition to lime considerable amounts of water must be available since the majority of the minerals are hydrous.

Marshall (1911) regarded the rodingites as primary products of crystallization while Finlayson (1909, p.358) considered the rocks to have been enriched in lime by the digestion of limestone in the gabbroidal magma.

Grange (1927) concluded that the rocks were derived from the alteration of gabbros, the garnet being secondary after calcic plagioclase.

Opinion at present favours the metasomatic introduction of lime into the rocks by the serpentinization of lime-rich pyroxene contained in the adjacent ultrabasic rocks (Miles, 1950).

Other lime-silicates introduced into the marginal rocks, in addition to garnet, are considered as having a similar origin. Watson (1942, 1953) records the introduction of prehnite, zoisite and diopside into basic and acid dykes (albitite) intrusive into peridotite, now serpentinized.

Associated with replacement phenomena are veins or dykes bearing lime-silicates. Murgoci (1900) records masses containing minerals such as grossularite, vesuvianite, fassaite, clinozoisite, lotrite (pumpellyite), clinochlore, diopside, as inclusions in the serpentinites of Rumania, while identical rocks have been described by Benson, 1918; Graham, 1917; Arshinov and Merenkov, 1930 and Turner, 1933.

In the case of the Byne Hill rodingites there is no evidence to suggest that the lime was derived from the serpentinization of clino-pyroxene in the ultrabasic rocks since the latter were harzburgites (olivine-bronzite).

Some lime may have been derived from the alteration of diallage in the gabbro itself but this would be quite insufficient in amount.

Although the rodingites and lime-silicate veins are closely associated with serpentinization, they are not formed from material removed from the peridotitic rocks during serpentinization. It is concluded that lime and other materials formed part of the hydrothermal solutions and gases which were responsible for producing serpentinization posterior to the consolidation of the ultrabasics and their intrusion by a later series of basic rocks.

Carbonation of the serpentinite, to be described in the next section, is regarded as an identical phenomenon involving hydrothermal alteration of the serpentinite.

VII. CARBONATE ROCKS AND ASSOCIATED SULPHIDE DEPOSITS:

(a) Mode of Occurrence:

Serpentinite, altered to almost pure carbonate rocks, occurs in some parts of the complex: in the southern belt at Knockdhu and Moak Hill and at North Ballaird and Byne Hill in the northern belt.

The carbonate rocks are generally associated with, and show gradations into, unaltered serpentinite.

In many cases the rocks are developed along lines of faulting and deformation (e.g. Byne Hill, N. Ballaird) but such a relationship is not always obvious in other localities where original serpentinite textures remain in the carbonated rocks (cf. Plate 25, A).

At Byne Hill the carbonate rock is associated with pyrites, this locality being once the site of a copper-mine.

(b) Nature of the Carbonates:

(i) Magnesium-Iron Carbonate:

Rock bearing this kind of carbonate occur at Moak Hill and Byne Hill.

Chemical and optical tests show that the carbonate mineral is a member of the magnesite-siderite series with more than 50% $FeCO_3$- breunnerite or mesitite (Winchell, 1951, p.109; du Rietz, 1935). These rocks may also carry a little dolomite.

(ii) Calcium Carbonate:

The development of this type of carbonate occurs in serpentinites at Knockdhu and North Ballaird.

(c) Petrography:

Rocks with Magnesium-Iron Carbonates:

(i) At Moak Hill the carbonate rock projects as a boss-like mass, some 50 feet high, above the level of the surrounding serpentinite. The rock retains the texture of the original harzburgite-serpentinite.

Bronzite crystals, pseudomorphed by a grass-green chlorite and carbonate are set in a dull grey groundmass of carbonates (Plate 34, A).

In thin sections the original texture of the rock (mesh-structure) has almost vanished, although abundant magnetite granules often preserve a vague mesh-like pattern. Elsewhere however the magnetite appears to have segregated into large irregular bodies.

Secondary quartz often forms a complex mosaic with carbonate granules.

Irregular grains of picotite are also present.

(ii) Exposed in a small stream at the base of the SE slope of Byne Hill are carbonate rocks which are strongly pyritized. No trace of an original texture remains due probably to the effects of deformation along a fault (Plate 2). Only the presence of fractured grains of picotite reveal its derivation from an ultrabasic rock (Plate 34, B).

Like the previous example the bulk of the carbonate is breunnerite or mesitite but more euhedral, zoned crystals of dolomite are also present.

Rocks with Calcium Carbonate:

(i) At Knockdhu the carbonate rock forms an E-W trending ridge about 50 yds. in length and is exposed in a roadside quarry by the Knockdhu Burn.

The rock at first sight appears to be brecciated, pinkish knots of calcium carbonate weathering out from a dark serpentinous groundmass. All gradations occur in the replacement of the serpentinite by calcium carbonate, which, in addition to irregular patches, forms a complex system of veins which tend to be sub-parallel (Plate 34, C, Plate 35, A).

The replacement of large bastite crystals can be observed; the fibrous structure remaining at an advanced stage of replacement. No distortion of the bastite occurs.

(ii) Rocks similar to the above are developed at the margin of a serpentinized dunite at North Ballaird. They differ in containing small fragments of altered diabase which are not carbonated (Plate 35, B).

Whether these fragments are inclusions in the serpentinite or the margin of the mass has suffered deformation can not be ascertained.

(iii) A small knob of carbonate rocks occurs in association with serpentinite at Knockormal. The rock is composed of large interlocking grains of calcite with occasional areas of anhedral quartz. No relict picotite could be detected so that the origin of the rock is obscure. Its mode of origin is quite different from a small lensoid mass of carbonate rock in lavas just to the SW (Fig. 2).

(d) Genesis:

(i) Rocks with Magnesium-Iron Carbonates:

The origin of these rocks presents little difficulty since, in the conversion of a peridotitic rock to serpentinite, some magnesia and probably iron must necessarily be liberated (p.118).

It is concluded that CO_2 forms an important constituent of the hydrothermal agents producing serpentinization of the ultrabasics, reacting with the excess magnesia and iron to form the magnesium-iron carbonates.

(ii) Rocks with Calcium Carbonate:

It is not easy to determine the source of large amounts of lime in the carbonated serpentinites. By analogy with the formation of rodingite (p.110) the lime must be derived from a source external to the ultrabasic rocks and not a product of their serpentinization.

Many carbonated ultrabasics have been regarded as simply phenomenon related to surface weathering or the effects of meteoric waters at lower levels (Knopf, 1904). However the occurrence in various parts of the world of large masses of completely carbonated ultrabasics suggests a different mode of formation.

Problems connected with the carbonation of a mica-peridotite dyke intrusive into shales and coals 200 feet

Table 13: Analysis of a Carbonated Mica-Peridotite Dyke:

SiO_2	14.48
TiO_2	1.56
Al_2O_3	5.44
Fe_2O_3	7.23
FeO	3.13
MnO	0.27
MgO	22.53
CaO	18.21
Na_2O	0.53
K_2O	0.45
H_2O +	8.46[x]
H_2O -	0.38
CO_2	17.51
P_2O_5	0.30
S	0.38
	100.86

[x] Loss on Ignition

S.G. 2.780

Carbonated Mica-Peridotite Dyke, Dixonville, Penna.

Honess and Graeber, 1926, p.6.

below the surface have been discussed by Honess and Graeber (1926). So abundant is the carbonate ($CaCo_3$) that it is regarded as primary, representing the last phases of the magmatic activity when the rock was attacked by rising carbonated waters (op.cit., p.4). In addition, the shale and coal (coked) marginal to the dyke are also thoroughly charged with dense carbonate.

An analysis of the carbonated mica peridotite dyke is given in Table 13 (cf. Table 12).

The possibility of distinguishing between carbonate of a primary (magmatic) origin and that of a secondary nature has been discussed by Baertschi (1951).

Primary carbonates are characterized by a low content of the heavy isotopes of oxygen and carbon expressed as O^{18}/O^{16} and $C^{13}/^{12}$, the standard of comparison being a sedimentary limestone.

A sample of carbonated serpentinite from the exposure at North Ballaird was analysed for the writer by Baertschi who determined the ratios as: $O^{18}/O^{16} = -12.0$ and $C^{13}/C^{12} = -2.5$. The closest approximation to these values is supplied by a carbonatite dyke from Alnö with $O^{18}/O^{16} = -13.2$ and $C^{13}/C^{12} = -2.8$.

On the evidence thus obtained Baertschi regards the carbonate in the sample as possibly precipitated from (?)magmatic water at a temperature of some 200°-250°C, noting that the ratios are rather high for the rock to be analogous with carbonatite.

It is inferred therefore that carbonation is a hydrothermal process involving the addition of lime and CO_2 to the serpentinite. Certain similarities exist in the mode of formation of the rodingites and the carbonation of the serpentinite, both involving lime metasomatism and desilication.

Probably only a short interval of time elapsed between the serpentinization of the ultrabasics and their local carbonation, the latter being a later phase of the same general period of hydrothermal activity, closing with the formation of ore minerals (cf. Lodochnikow, 1936).

VIII. THE PROBLEM OF SERPENTINIZATION

Serpentine is essentially a non-aluminous chlorite having the composition $Mg_6(OH)_8Si_4O_{10}$, but varying proportions of iron and aluminium are present in some members of the group. The three common serpentine minerals, antigorite, chrysotile and serpophite which differ in crystallographic and optical properties, are all represented in the Girvan-Ballantrae serpentinites.

Serpentinization may be conveniently considered under three headings: (a) the chemical reactions involved, (b) the source of the constituents which are introduced and (c) the destination of the constituents that are removed.

(a) The Chemistry of Serpentinization:

Several reactions have been postulated in the conversion of dominantly olivine-rich rocks into serpentinite (cf. Graham, 1917; Turner, 1948), and may be divided according to whether or not a change in volume is involved.

From evidence already given it appears likely that in this area replacement of the ultrabasics by serpentinite has been volume for volume, the probable chemical reaction involving addition of water and loss of magnesia and silica:

$$2Mg_2SiO_4 + 2H_2O + CO_2 \rightarrow H_4Mg_3Si_2O_9 + MgCo_3$$

This reaction produces a volume increase but if appropriate amounts of $MgCo_3$ are removed the reaction can be made volume for volume. In fact any simple equation which involves changes in volume can be made volume for

Table 14: Differences from Average Composition of Girvan-Ballantrae Serpentinite.
(Based on analyses recalculated to grams per 100 c.c.)

	1.	2.	3.	4.	5.
SiO_2	- 26.0	-17.0	-37.3	-39.1	-43.0
TiO_2	- 0.3	-	- 0.8	- 0.3	- 3.0
Al_2O_3	+ 2.6	- 2.5	- 3.1	-10.5	-14.9
Fe_2O_3	- 10.8	- 2.0	+ 7.5	+ 3.9	- 1.8
FeO	- 10.5	- 7.5	-15.5	-13.4	-27.0
MnO	- 0.5	-	- 0.3	- 0.6	- 0.6
MgO	- 51.0	-22.7	-32.9	-21.2	+62.6
CaO	- 1.7	- 4.8	- 2.8	-11.3	-50.7
Na_2O	+ 0.2	-	- 4.4	- 1.5	- 5.6
K_2O	- 0.6	-	+ 0.2	- 0.6	- 1.0
H_2O	+ 27.3	+20.3	+34.6	+33.1	+33.5
S.G.	3.29	3.07	3.27	3.23	3.20

1. Dunite. Daly, 1933, p.20.
2. Harzburgite. Johannsen, 1937, p.439.
3. Wehrlite. " " p.420
4. Lherzolite. Daly, op.cit.
5. Diallagite. " " " p.21.

(Specific gravities after Daly, op.cit. p.47).

volume by selecting certain values for each constituent (cf. Turner, 1948, p.130).

Since, however, the olivine in the Girvan-Ballantrae ultrabasics contains 25% fayalite, while magnetite (or haematite) occurs in the serpentinite, an equation of the following type is likely (Graham, op.cit.):

$$3Mg_3Fe\ Si_2O_8 + 3CO_2 + 4H_2O + O \rightarrow 2H_4Mg_3Si_2O_9 + Fe_3O_4 + 3Mg\ CO_3 + 2SiO_2$$

The removal of $Mg\ CO_3$ (magnesite) and silica produces a volume decrease of 8%.

Serpentinization of the bronzite in the harzburgites would follow lines similar to that of an iron-bearing olivine except that more silica would be liberated, possibly together with a little alumina and lime (cf. Dana, 1894, p.347).

The following table (Table 14) shows the amounts of material to be added or subtracted in deriving a serpentinite of the composition of that of the Girvan-Ballantrae area (Table 2) from ultrabasic rocks of various types, a volume for volume relationship being assumed.

In all rocks except diallagite, the main changes on serpentinization are loss of SiO_2 and MgO and a gain in H_2O. Considerable differences exist however in the amounts of these constituents added or subtracted when pyroxene is present. It is possible for example for an ultrabasic rock to exist which on serpentinization would involve neither a loss or gain in Mg O. The mode of such a rock would be olivine (Fo:Fa = 3:1) 28% and bronzite 72% (S.G. 3.25). However no such rock is present in the area.

In considering the changes brought about during serpentinization it is necessary therefore to make allowances for variations in the mineralogy of the ultrabasic rocks.

(b) Source and Nature of the Materials Introduced During Serpentinization:

Water is the most important constituent introduced in the serpentinization of all ultrabasic rocks. Gaseous materials including CO_2 are also probably introduced.

Either these materials formed part of the original ultrabasic magma or they were introduced subsequently from an external source.

A high content of water has been postulated to account for the existence of ultrabasic magma in the fluid state at temperatures far below the melting point of olivine. The water is assumed to be present in an amount sufficient to explain the serpentinization by a subsequent process of autometasomatism (cf. Benson, 1918; Foslie, 1931; Hess, 1933; Lodochnikow, 1936).

Evidence has already been presented (p.96) indicating that serpentinization of the Girvan-Ballantrae ultrabasics actually post-dated the intrusion of gabbros into the antecedent ultrabasic rocks. Thus, even if the water were present in sufficient abundance in the original magma it does not seem to have been directly involved in serpentinization. An external source for the agents of serpentinization appears therefore to be likely.

Two possible external sources have been suggested by workers on serpentinites, although these sources are not entirely independent.

The association of serpentinites with submarine lavas and marine deposits suggests that the water to produce serpentinization might be derived from the sea (cf. Holland, 1899; Steinmann, 1905; Benson, 1918). This leaves unexplained the origin of serpentinites of non-marine associations.

The absorption by peridotite of water from the adjacent rocks (geosynclinal sediments) has also been postulated (cf. Hess, 1938). The mechanism of absorption presents a difficulty in both these hypothesis, while in the second the quantity of water available is unlikely to be adequate.

In the Girvan-Ballantrae area, the available data, so far from suggesting that the adjacent rocks were dehydrated points to the activity of hydrothermal solutions beyond the limits of the serpentinite.

It is possible that the serpentinizing materials are related to hydrothermal activity associated with and following upon the intrusion of later basic rocks.

(c) Destination of those Materials Removed During Serpentinization:

Large quantities of magnesia must be removed from the ultrabasic rocks during serpentinization, together with silica. Some magnesia is represented in the carbonate rocks, but these are trivial in amount and sporadic in relation to the masses of serpentinite.

No satisfactory explanation for the absence of displaced magnesia in the bulk of the serpentinite or contact rocks can be given. It can only be assumed that the magnesia was removed in solution and possibly transported to higher levels. Post-serpentinite movement has also removed it from its original contact associations in the majority of cases.

In certain other regions (cf. Bain, 1924) the destination of magnesia and silica displaced during serpentinization is more easily ascertained, for important deposits of magnesite with associated opal and chalcedony have been formed by replacement of limestone or dolomite and as large bodies within the serpentinite itself (cf. Lodochnikow, 1936). Similar cases involving the dolomitization of limestones suggest the easy solution and movement of magnesia.

IX. ACID INTRUSIVE ROCKS

(a) Distribution:

Two masses of granite associated with gabbro and serpentinite are exposed at Grey and Byne Hills in the north-western part of the area (Plate 1 and 2).

(b) Field Relationships:

The granites form central elongated cores about which the gabbro is disposed. The southern margin of the gabbro abuts against serpentinite, the contact however is only sporadically exposed.

The northern margin is in contact with Benan conglomerate along most of its length except to the SW where the intrusive rocks are faulted against lavas.

Exposures at Grey Hill are very poorly developed and considerably weathered: they will not be considered further. The relationships are, however, identical with those at Byne Hill where the exposures are rather better. The rocks are, nevertheless, very much altered and brecciated and provide very poor material for thin sections.

Relationships between the serpentinite and gabbro of Byne Hill have been described previously together with details of the gabbro (pp.87-94).

With one exception the junctions between the serpentinite and gabbro are lines of movement along a series of north-easterly trending faults.

Except where faults intervene, the inner (northerly) boundary of the gabbro grades rapidly into diorite, through quartz-diorite to granite (trondhjemite). This relationship exists along the whole southern flank of the hill although towards the north-east the gabbro and diorite are cut out by faults which bring the serpentinite into juxtaposition with granite.

The form of the mass will become apparent following a description of the various rock types and their disposition. All the contacts however appear to be vertical or nearly so.

In order to study the relationships existing between the gabbro, diorite and granite a line of traverse was made up the flank of the hill from a point to the west of,

Table 15: Modal Analyses of Byne Hill Rocks:

VOL. %	1.	2.	3.	4.	5.
Quartz	-	-	-	17.0	30.2
Orthoclase	-	-	-	X	2.0
Plagioclase	49	60.2	62.7	63.0	57.9
Pyroxene	2	1.5	-	-	-
Hornblende	42	16.0	X	X	X
Chlorite	6	8.5	18.0	12.0	9.8
Biotite	-	2.0	14.0	5.5	-
Apatite	} 11	3.0	-	-	-
Ore		5.3	X	-	-
Calcite	-	-	5.3	2.5	X
Zircon	-	-	X	X	X
Total dark minerals	50	28	32	17.5	9.8

X Less than 1%

1. Altered gabbro, Byne Hill (p. 89)
2. Acidified gabbro, " . " (p. 125)
3. Basified granite, " " (p. 126)
4. " " " " (p. 126)
5. Granite " " (p. 127)

and parallel to, a north-west trending fault which downthrows to the north-east, (cf. Teall, 1899, pp.482-483; Tyrrell, 1933, p.71).

(c) Petrography

(i) Gabbro-Diorite:

A description of the gabbro has already been given together with two modal analyses (Table 10 and pp 88-89), one of which is repeated for comparative purposes in Table 15, 1.

Some 6 feet from the diorite the gabbro appears in hand specimen to be a normal ophitic gabbro (Plate 36, A). Thin sections however reveal the presence of dispersed shreds of deep brown biotite, often occurring in association with altered plagioclase or developing from chloritic material after hornblende (Harker, 1904, pp.122-123). Secondary albite-oligoclase is present and is probably derived from the primary plagioclase.

One foot away from the diorite there is an increase in the lighter constituents in the gabbro which nevertheless retains its textural identity (Plate 36, B). Biotite becomes more abundant while apatite, sparingly present elsewhere, becomes prominent. The ferromagnesian constituents are considerably reduced in amount and are generally chloritized. Some uralitic amphibole remains with occasional cores of unaltered pyroxene.

While there is a marked increase in plagioclase this may be due to the inherent variability of the relative amounts of the constituents in the original gabbro. The second generation plagioclase is however rather more sodic than previously with $Ab_{92}An_{8}$ (Plate 36, C).

A modal analysis of this rock is given in Table 15, 2.

Beyond this point radical changes in texture take place. The gabbroidal texture breaks down into isolated clots of felspar and dark minerals, still showing an ophitic relationship, the remainder of the rock assuming a xenomorphic granitoid texture (Plate 36, D). Occasionally pegmatitic veins carrying quartz, pink orthoclase and biotite traverse the rock (Plate 37, A).

Within a few inches the whole rock assumed a uniform granitoid texture.

Inthin sections the rock is xenomorphic-granular although the plagioclase is generally more euhedral. Its composition is $Ab_{95}An_{5}$ and quite fresh except for a fine dusting of sericitic material. The lack of altered cores and its uniform composition suggests that, unlike that in the previouslydescribed rocks, the plagioclase is an original sodic variety.

The dark minerals are deep red biotite, often altered to a spongy red vermiculite (Winchell, 1951, p.376). This alteration product has been included with biotite in the modal analysis given in Table 15, 3.

The rock appears to have contained amphibole which is all altered to chlorite or biotite, generally with the development of calcite pseudomorphs.

Apatite is quite absent, but for the first time zircon becomes a constant accessory, usually associated with the vermiculite (Plate 37, B).

While termed "diorite" the texture is more granitoid than dioritic.

The rock is regarded as a basified granite.

(ii) Diorite-Granite:

As the granite is approached there is a slight coarsening of the rock accompanied by a decrease in the dark minerals relative to the lighter constituents. Quartz becomes visible in hand specimens and one or two subhedral crystals of orthoclase can be seen in thin sections (Plate 37, C).

The rock corresponds to a quartz-diorite but with the same textural limitations as noted previously. The mode of the rock is given in Table 15, 4.

With increasing acidity large clumps of quartz weather out on the surface of the rock which passes into an albite-granite or trondhjemite.

Plagioclase with a composition $Ab_{95}Am_5$ tends to form idiomorphic crystals associated with stumpier orthoclase. It is probable that the original plagioclase may have been rather more basic since frequently turbid saussuritic cores can be seen. Indeed, if the rock is to be termed trondhjemite (Balsillie, 1932, p.128) the composition of the plagioclase should be oligoclase or andesine (Johannsen, 1937, p.387).

Quartz tends to occur in clumps producing some degree of irregularity in the overall texture of the rock (Plate 37, D, Plate 38, A).

Biotite and accessory zircon form the remainder of the rock, the mode of which is given in Table 15, 5.

(d) Hybridization:

It is considered that the rocks of intermediate composition have been formed by the introduction and exchange of material associated with the intrusion of a later mass of granite into an earlier intrusion of gabbro (cf. Harker, 1903, 1904; Tyrrell, 1928).

On the basis of textures alone distinctions can clearly be drawn in the field between acidified gabbro on the one hand and basified granite on the other.

While the transition from gabbro to diorite is tolerably abrupt, being accomplished over a horizontal distance of a few feet, it is nevertheless gradational

Table 16: Analysis of the Byne Hill Granite:

SiO_2	70.18
TiO_2	0.46
Al_2O_3	14.24
Fe_2O_3	0.16
FeO	4.64
MnO	-
MgO	0.71
CaO	1.44
Na_2O	6.09
K_2O	0.73
H_2O +	0.88
H_2O -	0.34
CO_2	-
P_2O_5	0.23
FeS_2	0.19
	100.29

Balsillie, 1932, p.129.

in detail. The passage into granite is much more gradual however and takes place over a distance of some 20 yards.

Unfortunately the extensive albitization, brecciation and weathering of the rocks on Byne Hill renders microscope determination difficult.

(e) Analyses:

In view of the altered nature of the rocks no new analyses have been made. One analysis of the granite (Balsillie, 1932) is given in Table 16. This rock is slightly basified however.

(f) Form of the Byne Hill Complex:

The form of the complex has been deduced from two main lines of evidence: (i) the disposition of the basified and acid granite and (ii) evidence supplied by faults.

(i) Areas of basified granite occur not only in association with the present outcrops of gabbro and diorite, but also on the northern flanks of the hill where no basic rocks are exposed (Plate 2). This suggests that the basic rocks originally formed a complete mantle around the granite, a relationship which is evident from the disposition of the rocks at Grey Hill to the SW.

(ii) The width of outcrop of the diorite is variable, tending to widen near a point immediately to the south of the summit of the hill where its topographic height approaches that of the granite at the summit.

Furthermore, granite on the west side of a NW trending fault passing just to the west of the summit of the hill is never basified and attains the highest degree of acidity (Fig. 7).

It is concluded therefore that the complex is arcuate in form, granite occupying the core and originally lying beneath the diorite and gabbro, forming a roof. This is also indicated by the increase in the amount of basified granite cropping out towards the NE, suggesting that higher levels (roof zone) are being exposed; the whole mass pitching to the NE.

(g) Faulting:

Two main systems of faults occur: (i) a north-easterly group parallel to the general trend of the rocks and (ii) a north-westerly trending system.

(i) The north-easterly group are either strike faults or reverse faults. In no case is it possible to demonstrate the precise nature of the fault. However Lapworth (1882, p.579) regarded them as high angle reverse faults based on evidence obtained from other parts of the Southern Uplands where thrust faulting is widely developed. This interpretation is also adopted in the present account.

Two large reverse faults occupying the northern and southern flanks of the intrusion bring the younger Benan conglomerate into contact with granite and serpentinite respectively.

The line of the northern fault is marked by a topographic depression and by considerable cataclasis of the Benan conglomerate and granite, the latter being frequently strongly haematized in the vicinity of the dislocations.

The southern fault is less well exposed, but its line probably occupies a topographic depression running between Byne Hill and an elongated ridge of Benan conglomerate to the south.

Smaller reverse faults traverse the igneous rocks themselves causing gabbro and diorite to be progressively eliminated towards the NE. These faults produce varying degrees of cataclasis in the igneous rocks.

(ii) The precise nature of the NW set of faults is also uncertain. Some are probably tear faults associated with the reverse faulting. Two of the larger faults however produce considerable vertical displacements in the rocks.

The largest of these is apparently that which serves to define the south-western margin of the intrusion and is probably bringing up the whole intrusion from a lower level, suggesting the possibility that the Grey and Byne Hill granites are continuous with a common NE pitch (Plate 38, B, C).

Parallel to this fault is another passing just to the west of the summit of the hill. This fault, which has been mentioned previously, downthrows to the north-east, bringing highly acid granite into juxtaposition with basified granite.

X. PETROCHEMICAL ASPECTS:

All the available analyses of the Girvan-Ballantrae rocks have been plotted on a ternary diagram in terms of various oxides (Figs. 8, 9).

Analyses of the diabases (Table 10, p. 89) and granulites (Table 8, p. 72) agree rather closely, especially in the rather high proportions of TiO_2 and Na_2O. However Al_2O_3 and Mg O are, with one exception, higher in the granulites.

The average value for Ca O in both rocks is about the same but the ratio of Mg O: Ca O varies from 0.58:1 to 0.55:1 in the diabases to almost 1:1 in the granulites.

Chemically the glaucophane-schists (Table 3, p. 42) resemble the granulites but carry less alkalies and more Fe_2O_3 and Ca O.

It will be seen in Fig. 8 that no significant separation exists between the fields occupied by diabase, granulite and glaucophane-schists. In fact there is a tendency towards overlap.

Although no conclusive evidence is forthcoming it is considered likely that the metamorphosed basic rocks (granulites, glaucophane-schists) formed part of the same general series of Arenig basic intrusive rocks of which the diabases are the only unmetamorphosed members which have been analysed.

Evidence already presented suggests that Ca O and Mg O are the oxides most likely to show significant variations since many of the rocks are affected by lime metasomatism or might be expected to exhibit changes of Mg O in connection with their metamorphism by the peridotite or later processes of serpentinization.

To illustrate the changes in Ca O and Mg O the rocks are plotted on a ternary diagram in terms of Al_2O_3, Ca O and Mg O (Fig. 9).

It is evident that, indeed, two principle trends are present; one towards increasing Ca O culminating in rodingite and the other towards higher Mg O (granulites).

However, since the metamorphic rocks have been subjected first to thermal metamorphism and later to the effects of serpentinization, it is not possible to assign the alteration to any single process.

XI. SUMMARY OF THE IGNEOUS AND METAMORPHIC HISTORY OF THE GIRVAN-BALLANTRAE COMPLEX:

The oldest rocks in the district are the Arenig spilitic lavas, tuffs, agglomerates and associated radiolarian cherts and sedimentary rocks.

Peridotite was intruded into the lower levels of the volcanic series, possibly along the lines of earlier dykes and fissures disrupting and metamorphosing the lavas and associated intrusives, many of which became included in the ultrabasic rocks (granulite, glaucophane-schists).

The peridotitic rocks and lavas were intruded by pyroxenite dykes.

Access of the peridotitic magma to these levels was facilitated by continuous deformation and downbuckling of the thick volcanic pile (cf. Hess, 1938, etc.).

Following the consolidation of the peridotite a series of later basic rocks were intruded, mainly into the ultrabasics but also into the lavas. These basic rocks possess chemical affinities with the metamorphosed basic rocks.

Locally acid rocks, presumably differentiates of the basic magma, intruded and hybridized the earlier basic intrusives.

Serpentinization of the ultrabasic rocks followed the intrusion of the later basic rocks. The water and other materials producing serpentinization were not constituents of the peridotitic magma but hydrothermal solutions and gases introduced from an external source. These hydrothermal agents may have been connected with, and followed upon, the intrusion of the basic rocks.

The basic rocks intrusive in the peridotite have also suffered serpentinization at their margins and are intruded by serpentinite. A similar relationship exists between serpentinite and lavas in one locality (Pinbain).

In many cases the intrusive relationships of the serpentinite are clearly tectonic (post-serpentinite). Others however suggest that during serpentiinization the ultrabasic rocks became comparatively mobile and under regional deformational pressure were capable of intruding and replacing the marginal rocks.

Textural evidence also indicates some degree of mobility (flow banding) in the serpentinite which may have migrated upwards by a process analogous to the "cold" intrusion of salt diapirs, still carrying inclusions of the rocks metamorphosed at lower levels, but in juxtaposition with unmetamorphosed rocks at its present margins.

During the "cold" intrusion of the serpentinite further marginal shearing and dislocation occurred. Some unmetamorphosed gabbros and sheared spilites, apparently inclusions in the serpentinite, may represent rocks disrupted and included in the serpentinite during this phase of intrusion (Knockormal).

In addition to serpentinization of the marginal rocks there is evidence of the introduction of large amounts of lime and water in the form of calcite, prehnite, epidote and grossularite (rodingite). The source of the lime is attributed to magmatic waters persisting posterior to the main serpentinization and producing local carbonation of the serpentinite and the development of sulphide ores. Lime-silicate veins also traverse the serpentinite.

After the close of igneous activity the igneous complex was subjected to two periods of folding, the first pre-Bala and the second Caledonian. It is probable that the earlier movements were, at least in part, contemporaneous with the igneous activity.

During these movements the igneous rocks suffered considerable deformation and faulting, large movements taking place along the serpentinite boundaries.

While these movements produced strong deformation in the serpentinite, the adjacent lavas and intrusions, being more resistant, show comparably less deformation.

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ILLUSTRATIONS

AND

DIAGRAMS

Fig. 1: Section across the whole Girvan-Ballantrae Complex based on Bailey's interpretation of the structure.

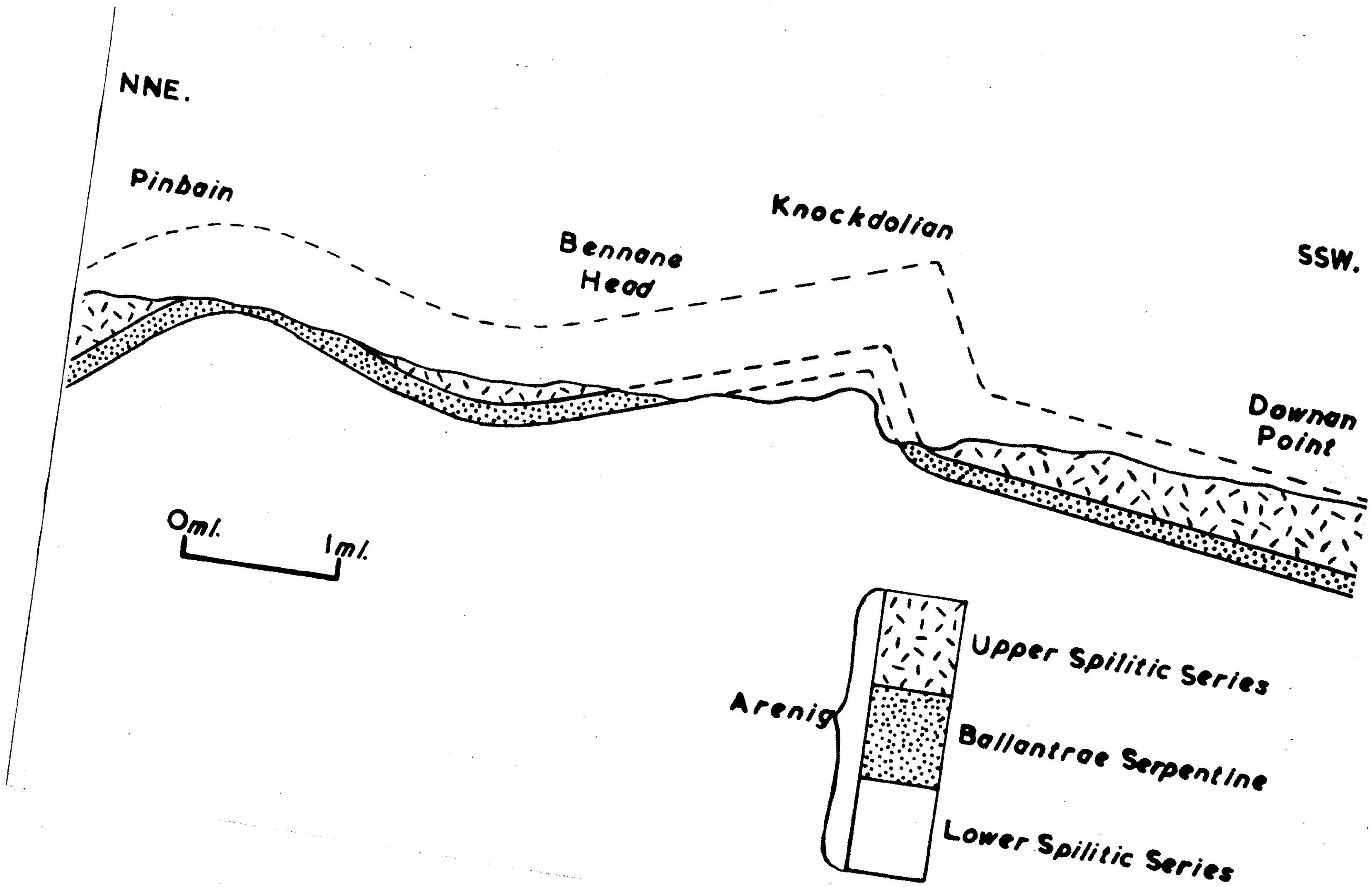
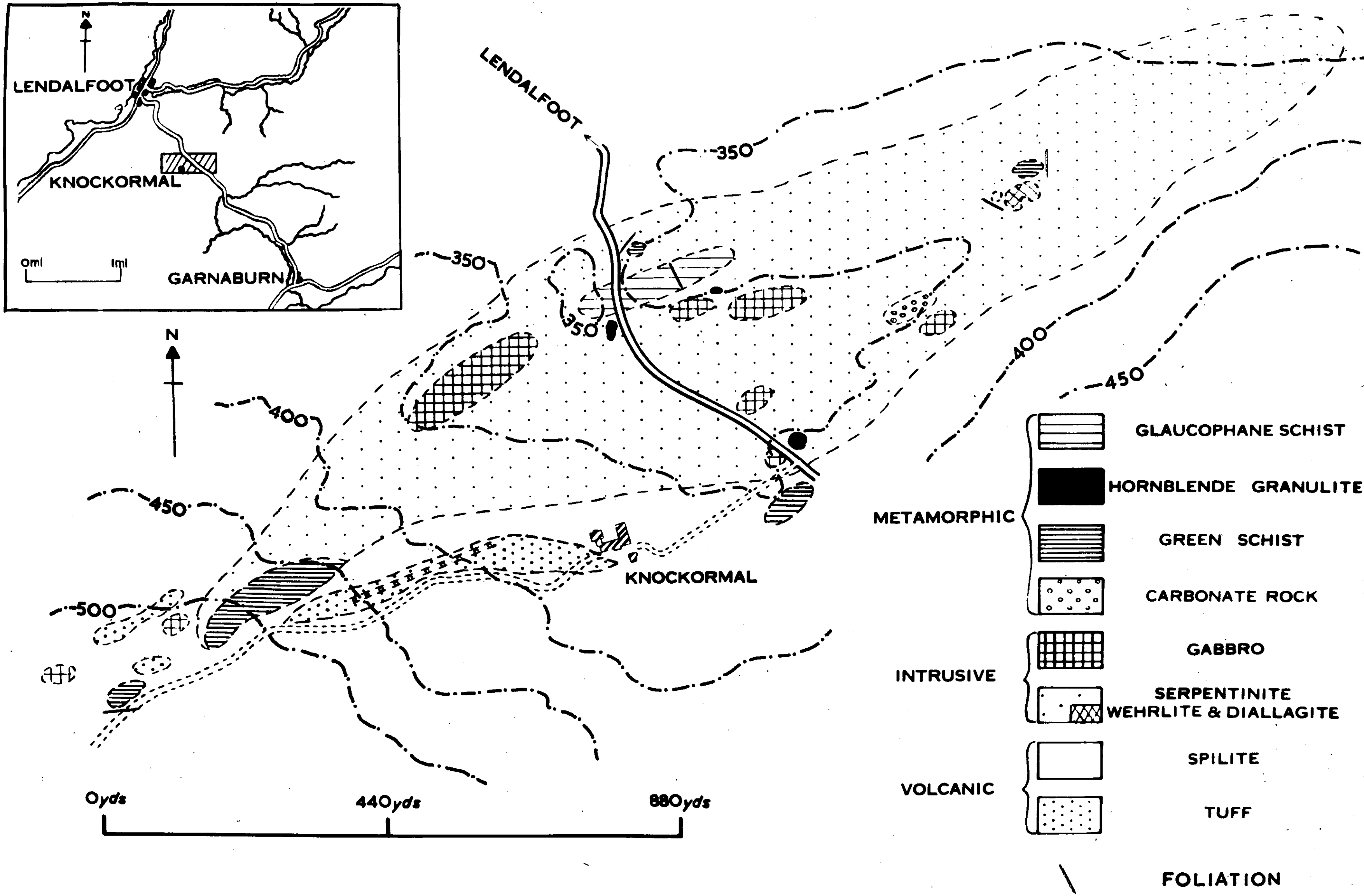
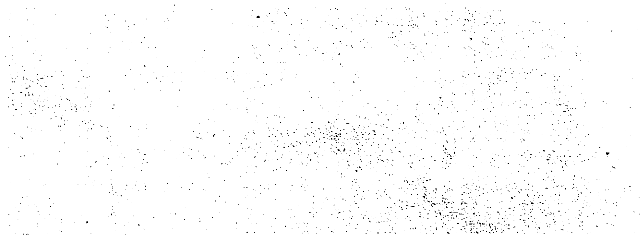
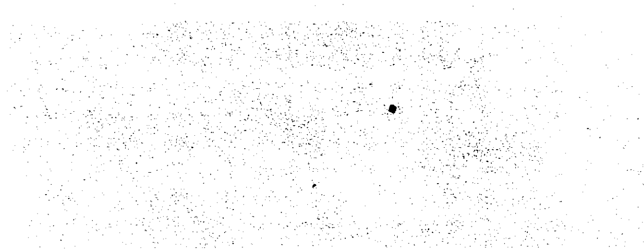

NNE.
Pinbain
Bennane Head
Knockdolian
SSW.
Downan Point
0ml.
1ml.
Upper Spilitic Series
Ballantrae Serpentine
Lower Spilitic Series
Arenig

Fig. 2: Geological map of the Knockormal glaucophane-schist locality. The small mass of eclogitic rock is shown as a small unornamented circle immediately beside the exposure of pyroxenite. Reduced from a scale of 25 ins. to 1 mile.


LENDALFOOT
KNOCKORMAL
GARNABURN
Oml
Iml
N
LENDALFOOT
350
350
350
400
450
400
450
500
KNOCKORMAL
Oyds
440yds
880yds
GLAUCOPHANE SCHIST
HORNBLENDE GRANULITE
METAMORPHIC
GREEN SCHIST
CARBONATE ROCK
GABBRO
INTRUSIVE
SERPENTINITE
WEHRLITE & DIALLAGITE
SPILITE
VOLCANIC
TUFF
FOLIATION



<u>Fig. 3:</u> Optic orientations of hornblende (plain) and glaucophane (stippled).



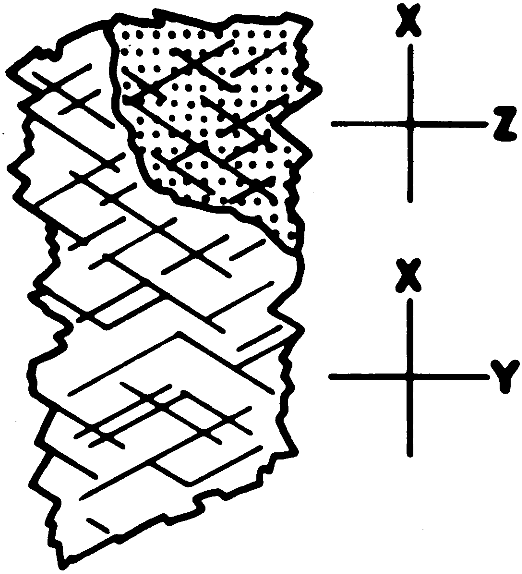

X
Z
X
Y

Fig. 4: ACF diagram of the analyses of the Knockormal glaucophane-schists and gabbro:

1. Altered gabbro } Table 11

2. "Glaucophane-gabbro"
3. Glaucophane-schist
4. Hornblende-schist
5. Washington's average basic glaucophane-schist

} Table 3

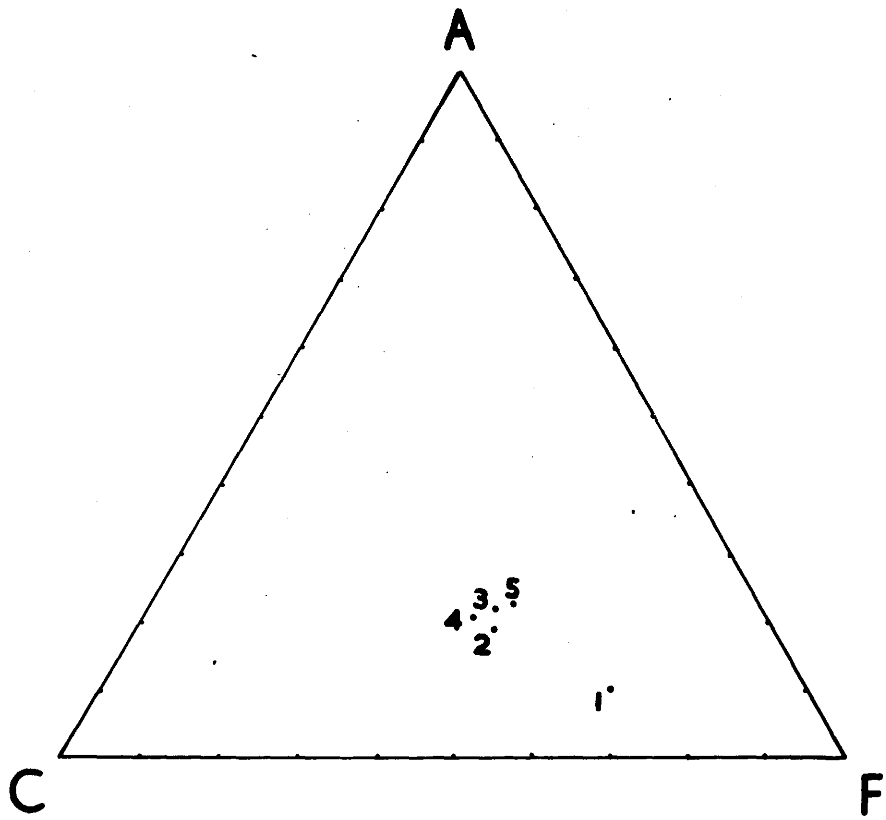
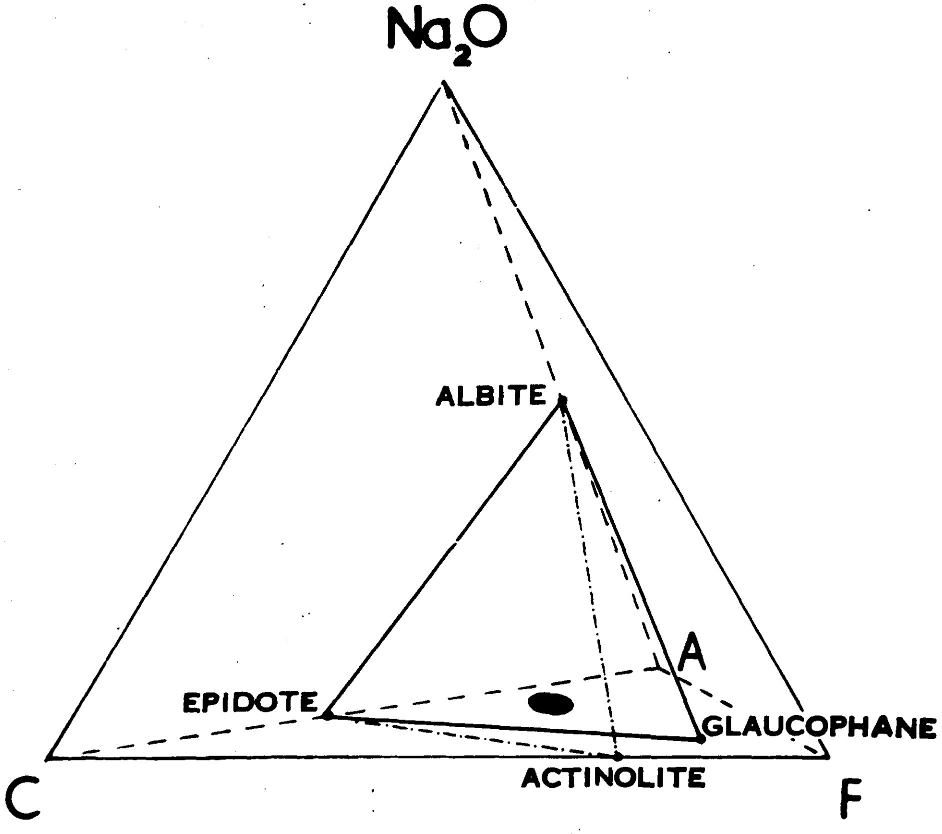

A
C
F
4
3
5
2
1

Fig. 5: Tetrahedral diagram showing the position of the field albite - epidote - glaucophane. The oval dark area lies on the plane of the above field and embraces the compositions of the Knockormal glaucophane-schists and Washington's average basic glaucophane-schist.


Na_2O
ALBITE
A
EPIDOTE
GLAUCOPHANE
ACTINOLITE
C
F

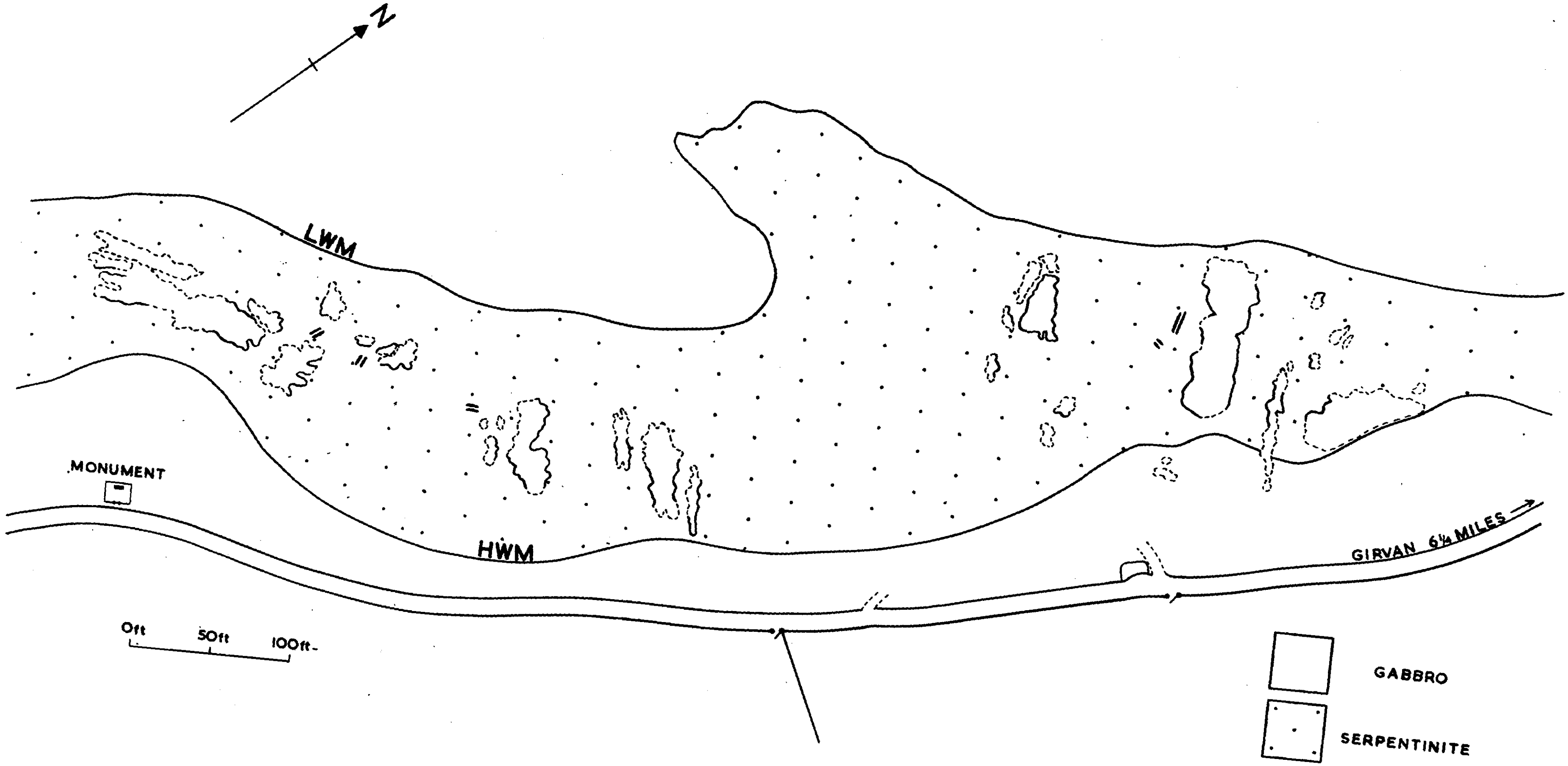

N
LWM
HWM
MONUMENT
0ft
50ft
100ft
GIRVAN 6¼ MILES
GABBRO
SERPENTINITE

Fig. 7: Vertical section through the Byne Hill Complex along line A-B (Plate 2). Scale 25 ins. to 1 mile.

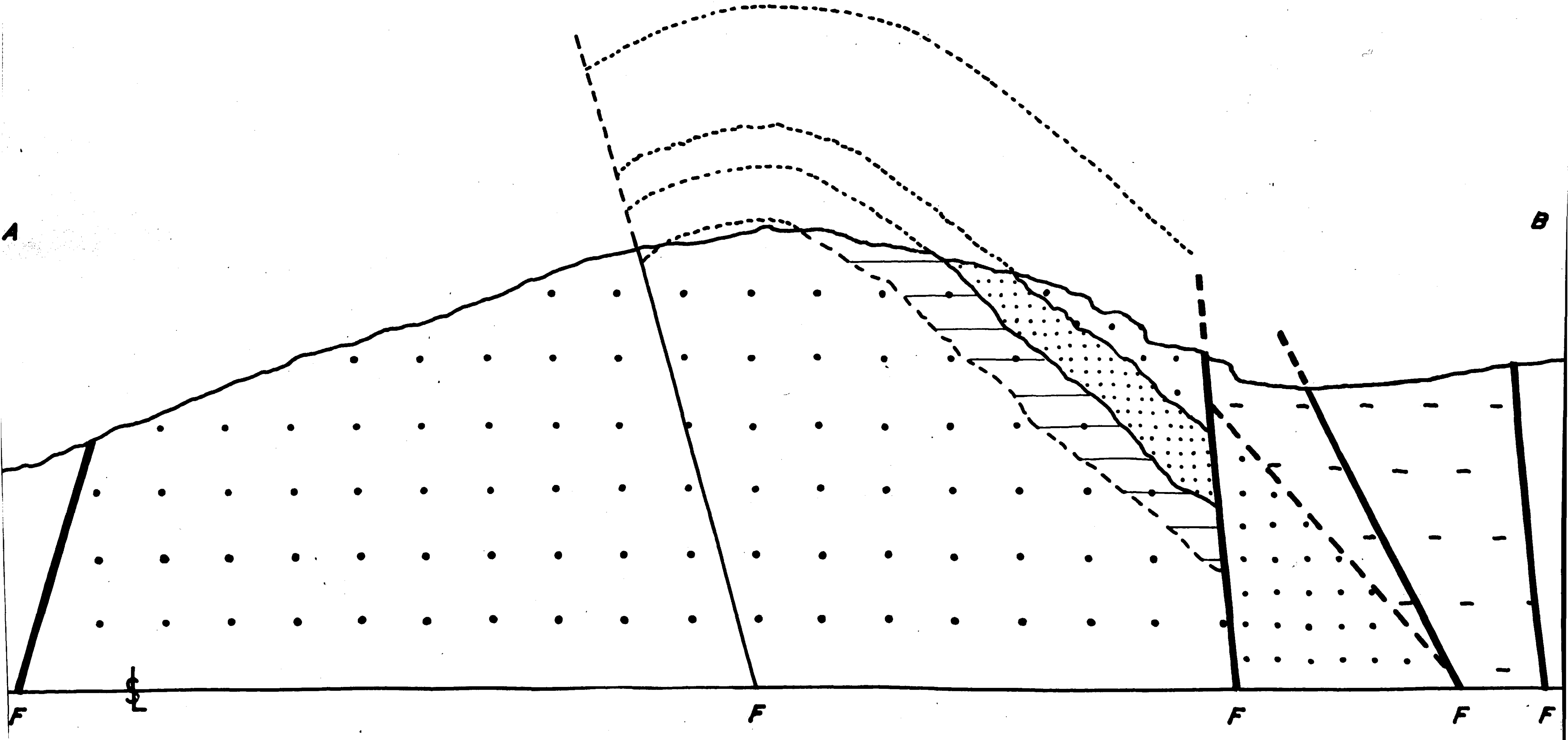
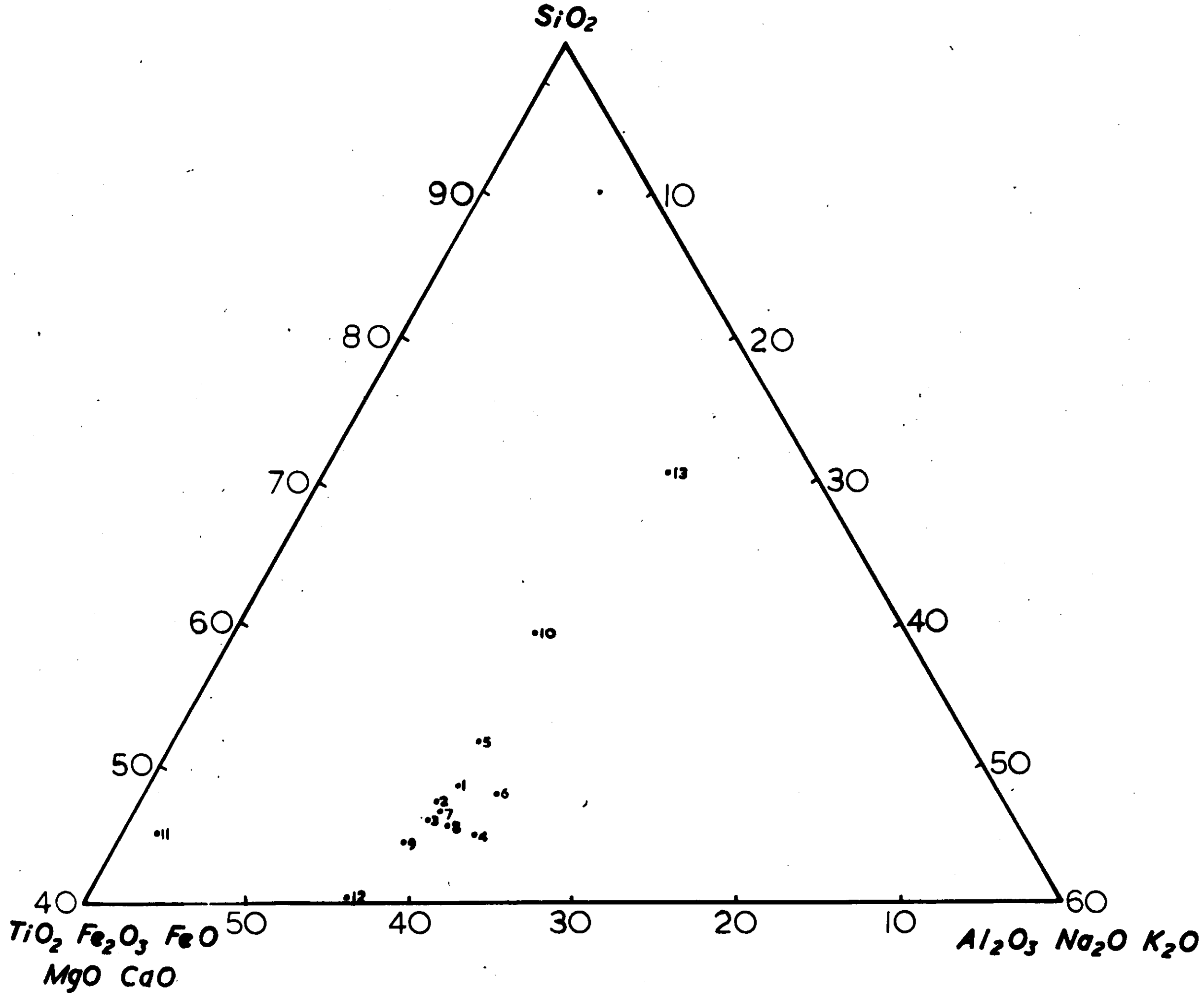

A
B
F
F
F
F
F

Fig. 8: Analyses of the Girvan-Ballantrae Rocks plotted on a ternary diagram:

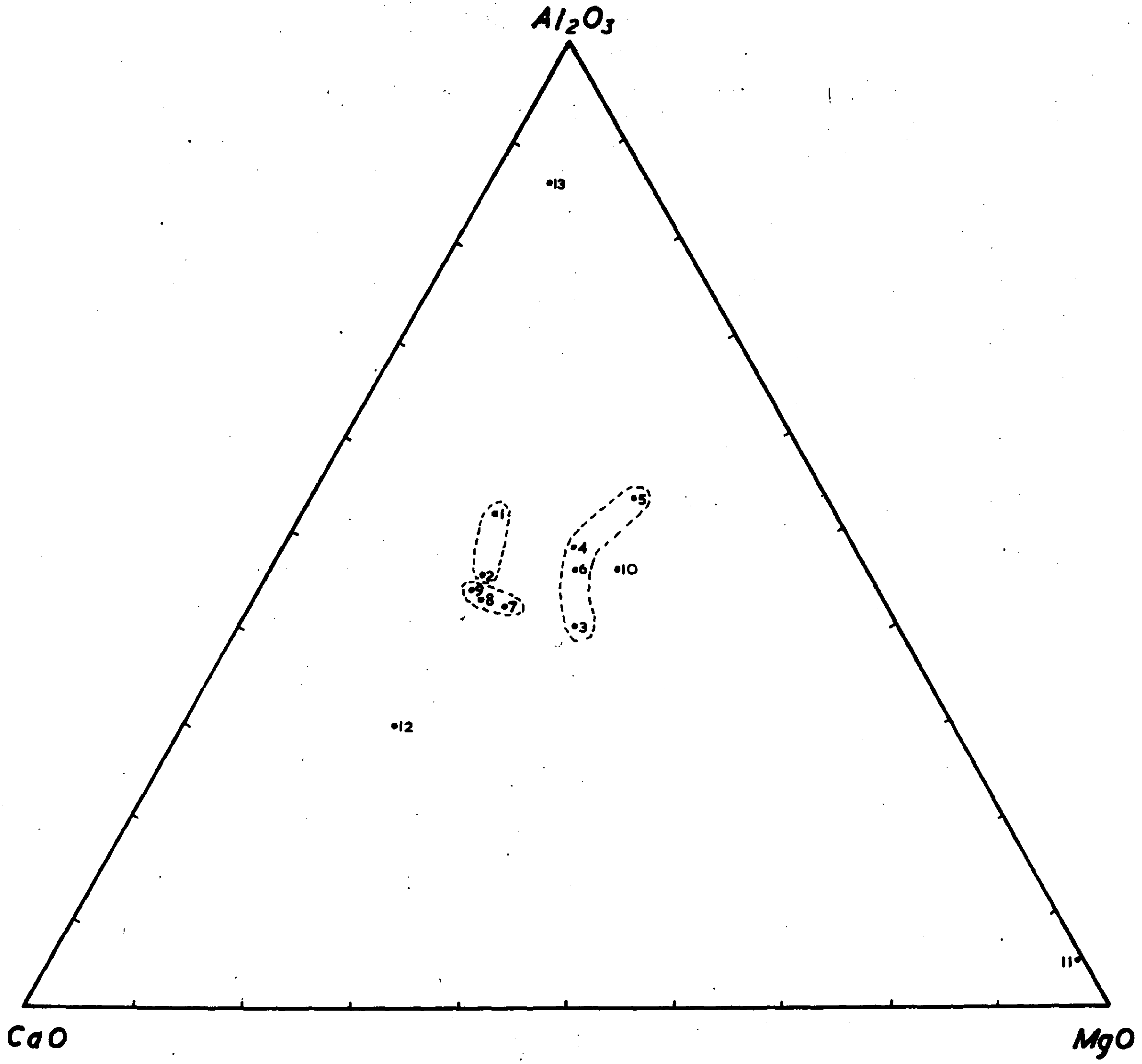
1.	Diabase	Table 10
2.	"	
3.	Granulite	Table 8
4.	"	
5.	"	
6.	"	
7.	Glaucophane-schist	Table 3
8.	"	
9.	"	
10.	Altered gabbro	Table 11
11.	Serpentinite	Table 2
12.	Rodingite	Table 12
13.	Granite	Table 16



SiO2
90
80
70
60
50
40
10
20
30
40
50
60
50
40
30
20
10
TiO2 Fe2O3 FeO
MgO CaO
Al2O3 Na2O K2O
1
2
3
4
5
6
7
8
9
10
11
12
13

<u>Fig. 9</u>: Analyses of the Girvan-Ballantrae rocks plotted on a ternary diagram in terms of Al_2O_3, CaO, and MgO:

(Plots as in Fig.8)



Al2O3
13
1
5
4
6
10
2
9
8
7
3
12
11
CaO
MgO

MAPS

Plate 1: Geological Map of the Girvan-Ballantrae Complex. Scale: 2½ ins. to 1 mile. (Rear folder).

Plate 2: Geological Map of the Byne Hill Igneous Complex. Scale 25 ins. to 1 mile. (Rear folder).

Plate 3: ULTRABASIC ROCKS

A. Sheared serpentinite at Burnfoot. Rotten foliated serpentinite enclosing ellipsoidal masses of unsheared serpentinite.

B. Cobbles of coarse altered gabbro included in deformed serpentinite; Burnfoot.

C. Position of sheared junction between websterite dyke and shattered lava to the left of the picture; Breaker Hill.

Plate 4: GRANULITIC ROCKS

A. Banded granulite; Poundland Burn. Alternating bands rich in hornblende and diopside, the latter rather schistose. The line of the knife and pencil marks a vein of serpentinite intruding the mass. At the top right a vein of diopside-zoisite traverses the rock.

B. Large knolls of flasered gabbro and associated granulite rising above the serpentinite; Millenderdale.


A


B

Plate 5: DIABASE INTRUSIONS; LENDALFOOT

A. Large diabase dyke intruding serpentinite. Patches of serpentinite adhere to the walls of the diabase.

B. Small diabase dyke intruding serpentinite.

C. Small diabase dyke intruding serpentinite.

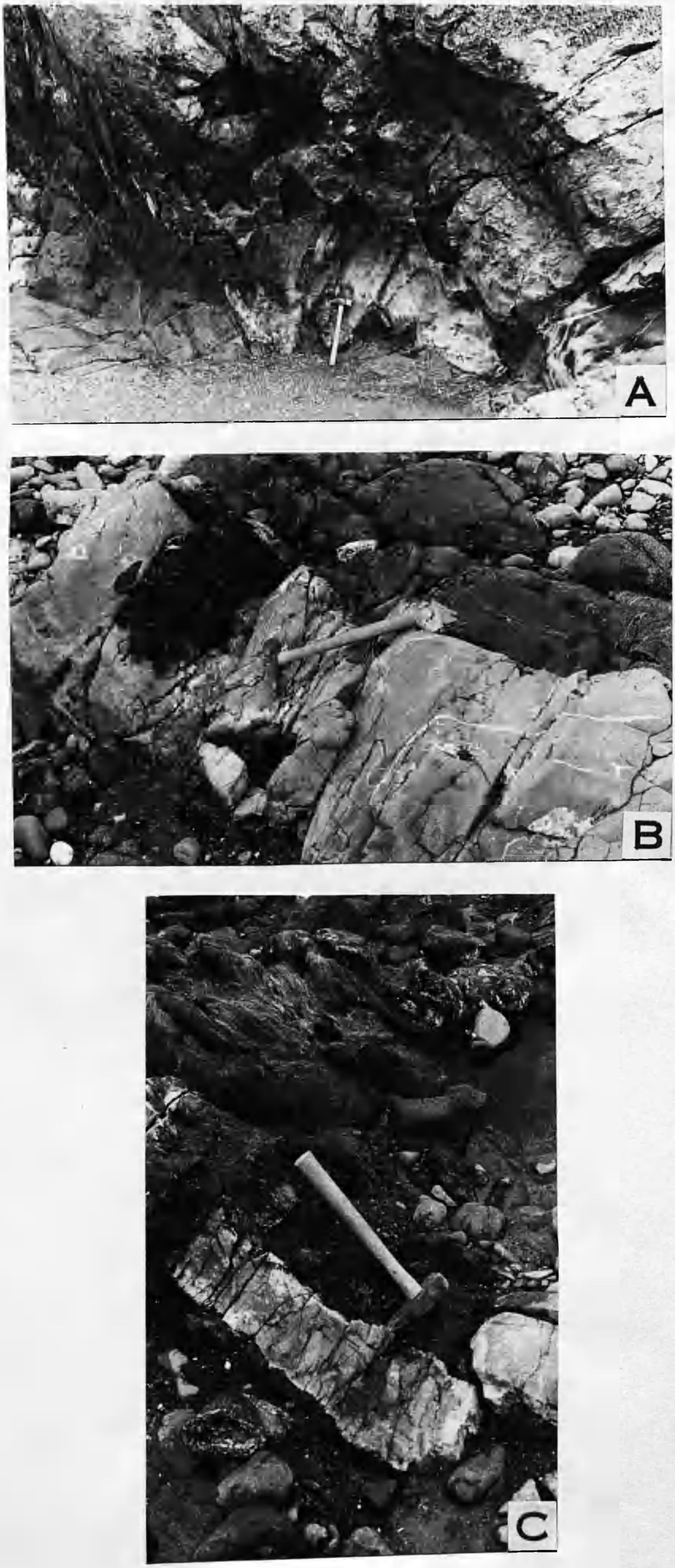

A
B
C

Plate 6: DIABASE INTRUSIONS; LENDALFOOT

A. Veins of serpentinite branching intrusively into unsheared marginal diabase.

Plate 7: GABBRO SERPENTINITE CONTACTS; BYNE HILL

A. Steeply dipping contact between serpentinite (dark) and chilled marginal gabbro (light). The serpentinite is caked onto the gabbro and adheres along depressions in the latter (left foreground).

B. Serpentinite interfingered with marginal phase of gabbro (light). One contact is indicated by the pencil point.

Plate 8: GABBRO INTRUSIONS; PINBAIN

A. Blocks of serpentinite included in coarse pegmatitic gabbro.

B. Vein-like apophyses from gabbro branching intrusively in serpentinite and diallagite.


A


B

Plate 9: GABBRO DYKES; BURNFOOT

A. Gabbro dykes varying in width from 10 ins. to ½ ins. cutting serpentinite.


A

Plate 10: LIME-SILICATE VEINS; POUNDLAND

A. Vein of diopside-zoisite rock traversing serpentinite.


A

Plate 11: LAVAS

A. Porphyritic spilite; Knockdolian.

Plagioclase phenochrysts and calcite-filled vesicles lying in a groundmass of plagioclase, chlorite and glass.

(OL. x 30)

B. Spilite; Bennane Head.

Plagioclase laths and interstitial chlorite and magnetite make up the major part of the rock. Two large calcite-filled vesicles are prominent.

(OL. x 30)

C. Amphibolized spilite adjacent to serpentinite; N. Ballaird.

The chloritic groundmass has been largely converted to fibrous amphibole.

(OL. x 30)


A


B


C

Plate 12: ULTRABASIC ROCKS; SERPENTINITES

A. Serpentinized harzburgite; typical of the whole area. Cores of dusty serpophite lie within a mesh-work of antigorite and magnetite. A crystal of bastite after bronzite is visible at the top left.

(OL. x 30)

B. Same field as above; nicols crossed. Antigorite surrounding isotropic cores of serpophite.

C. Haematized serpentinite; Burnfoot.

Serpophite cores and magnetite granules in the antigorite converted to reddish haematite. Fresh crystals of bronzite remain.

(OL. x 30)

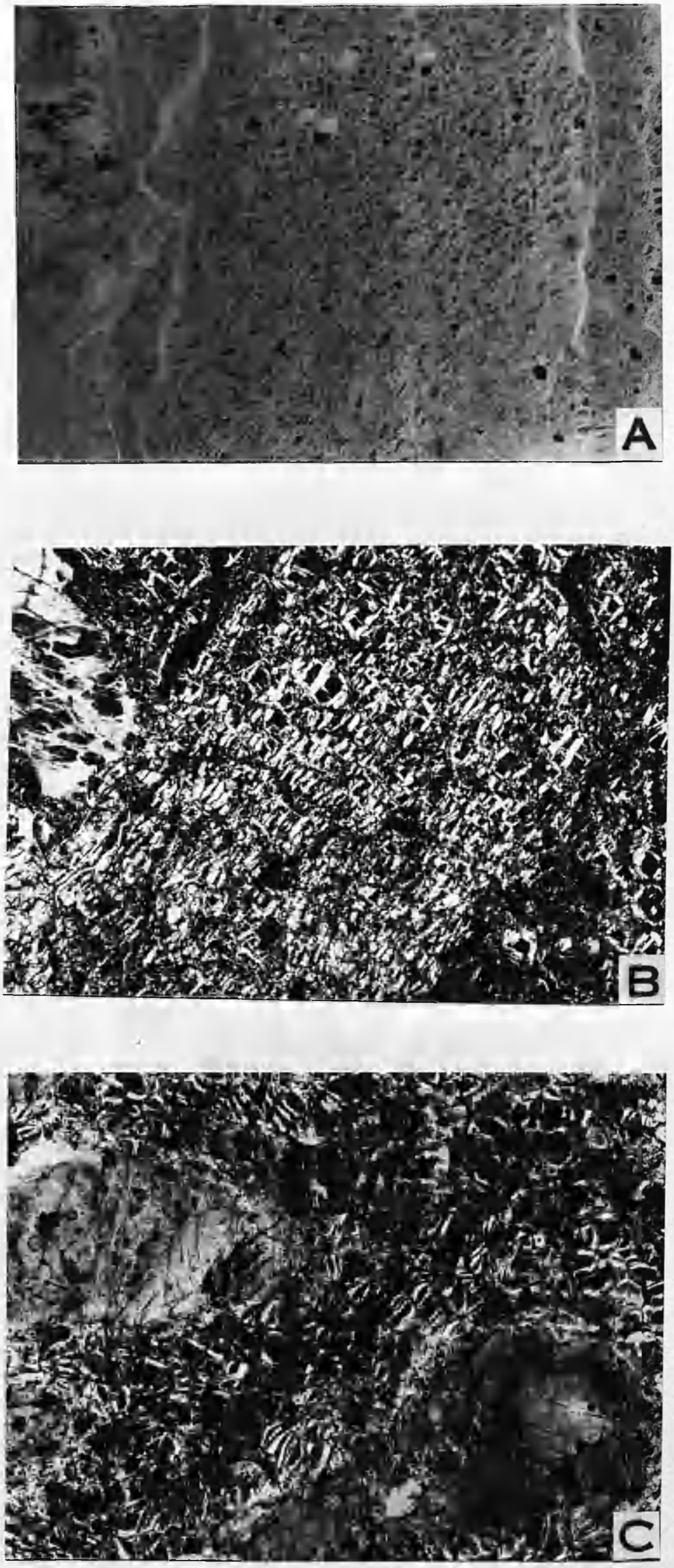

A
B
C

Plate 13: ULTRABASIC ROCKS; SERPENTINITES

A. Flow-banding in serpentinized harzburgite deflected around basite pseudomorphs after bronzite; Littleton Hill.

(XN. x 30)

B. Primary mineral banding in partially serpentinized olivine-pyroxene bearing ultrabasic. The dense strongs of magnetite are associated with the olivine-rich bands; Cairn Hill.

(OL. x 10)

Plate 14: DUNITE AND "PICRITE"

A. Partially serpentinized dunite; Knockdhu.

Relict cores of olivine in a developing mesh structure of serpentine and magnetite. A large grain of picotite occurs at the bottom left.

(OL x 30)

B. Partially serpentinized dunite; N. Ballaird.

The large colourless areas are serpophite.

(OL. x 30)

C. Serpentinized olivine-pyroxene rock; Breaker Hill.

Bulk of the rock composed of serpentinized olivine. The turbid areas are altered pyroxene (Picrite of Teall).

(OL. x 20)

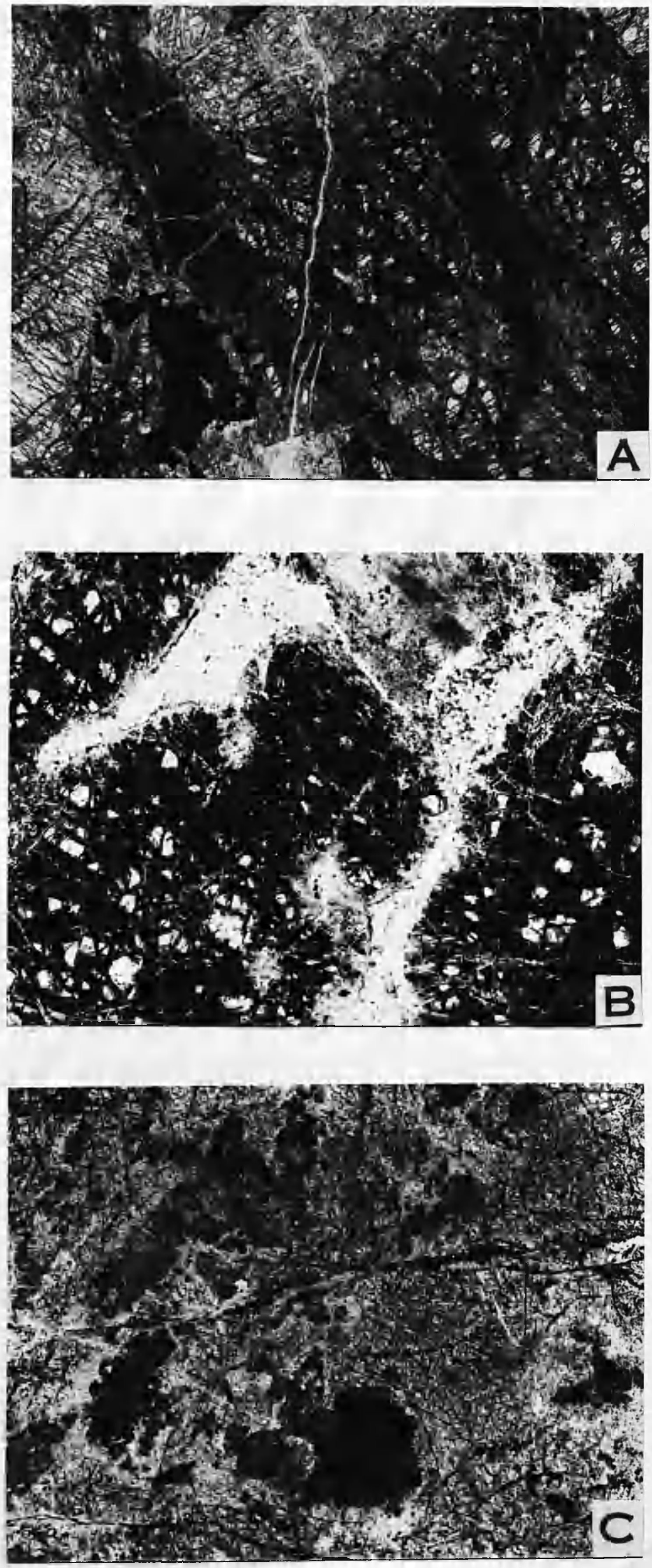

A
B
C

Plate 15: ULTRABASIC DYKES; PYROXENITES

A. Lherzolite; Lendalfoot.

Large crystals of diallage, often enclosing rather euhedral orthopyroxene are abundant. Partially serpentinized olivine occupies the central portion of the field.

(OL. x 10)

B. Wehrlite; Knockormal.

Olivine-diallage rock.

(OL. x 30)

C. Wehrlite; Knockormal.

Rather finer grained and the majority of the olivine is serpentinized.

(OL. x 30)

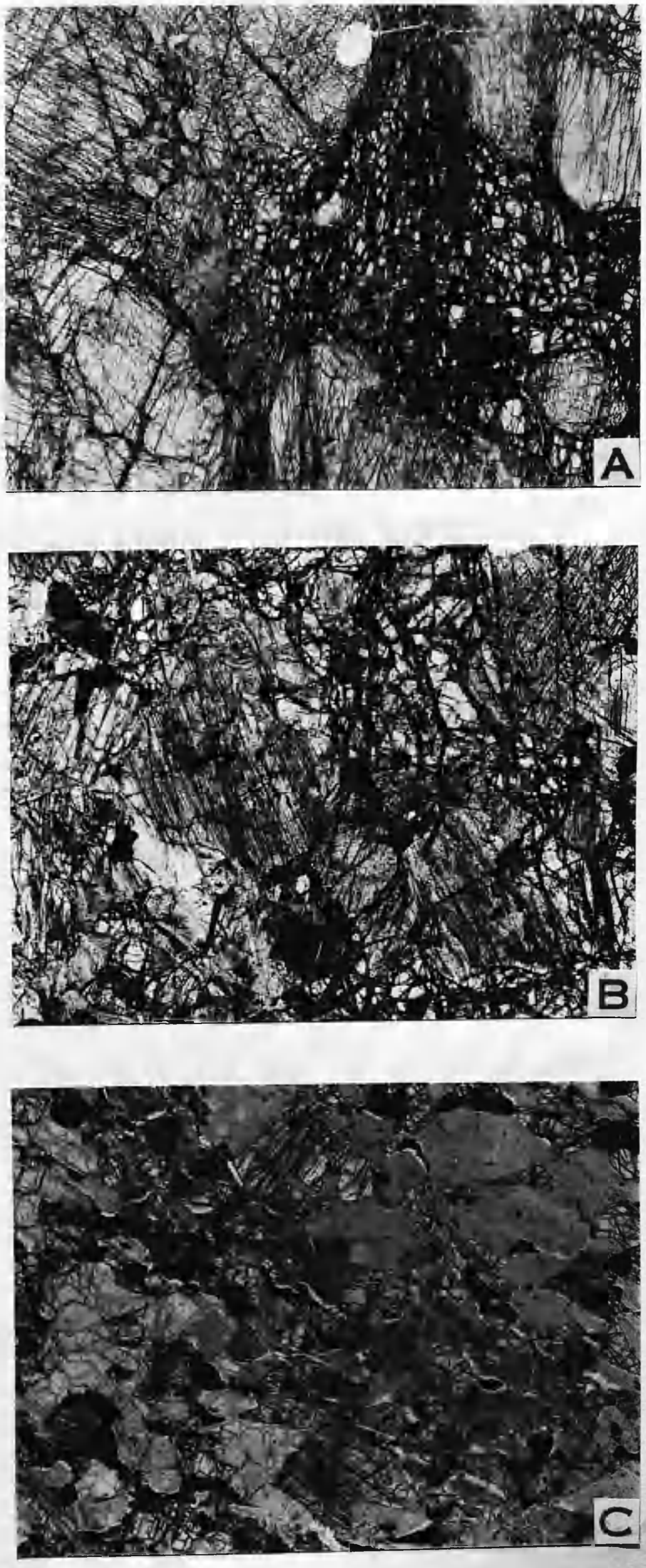

A
B
C

Plate 16: ULTRABASIC DYKES; PYROXENITES

A. Pyroxenite (diallagite); Knockormal.

The rock consists almost entirely of large plates of diallage, many of which exhibit cataclysis or bending.

(OL. x 20)

B. Websterite; Breaker Hill.

Large plates of diallage and smaller, partially serpentinized, crystals of orthopyroxene.

(OL. x 30)


A


B

Plate 17: GLAUCOPHANE-SCHISTS AND ASSOCIATED ROCKS; KNOCKORMAL

A. Epidote-hornblende-schist.

Hornblende porphyroblast deflecting a finer grained schistose groundmass of epidote and hornblende.

(OL. x 30)

B. Epidote-hornblende-glaucophane-schist.

The centre of the field is occupied by a large crystal of hornblende marginally altered to (lighter) glaucophane. Dusty, almost opaque epidote is abundant.

(OL. x 30)

C. Epidote-hornblende-glaucophane-schist.

Finer grained variety with clear epidote. Strings of almost opaque granular sphene occur.

(OL. x 30)


A
B
C

Plate 18: GLAUCOPHANE-SCHISTS AND ASSOCIATED ROCKS; KNOCKORMAL

A. Prehnite vein "shot" with fibres of actinolite cutting glaucophane-schist.

(OL. x 30)

B. "Glaucophane-gabbro". Large crystals of epidote and hornblende with marginal glaucophane are conspicuous. Streaks and patches of colourless albite are also present. No schistosity is developed.

(OL. x 30)

C. Fine grained garnet-glaucophane-schist.

(OL. x 30)

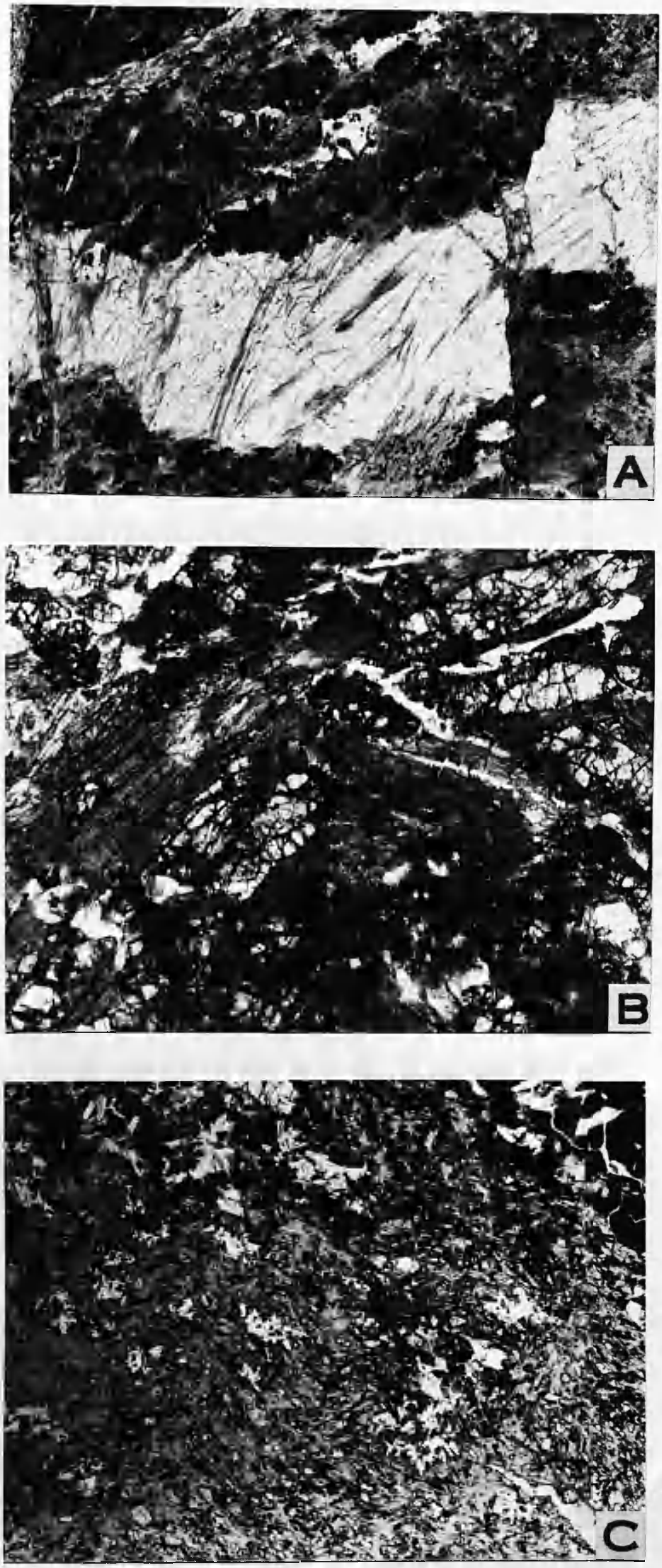

A
B
C

Plate 19: GLAUCOPHANE-SCHISTS AND ASSOCIATED ROCKS; KNOCKORMAL

A. Band of asbestiform glaucophane in greenschist. Associated with the glaucophane is actinolite, albite and peculiar "spherulitic" epidote crystals.

(OL. x 30)

B. Greenschist (Albite- epidote-chlorite-actinolite).

(XN. x 30)


A


B

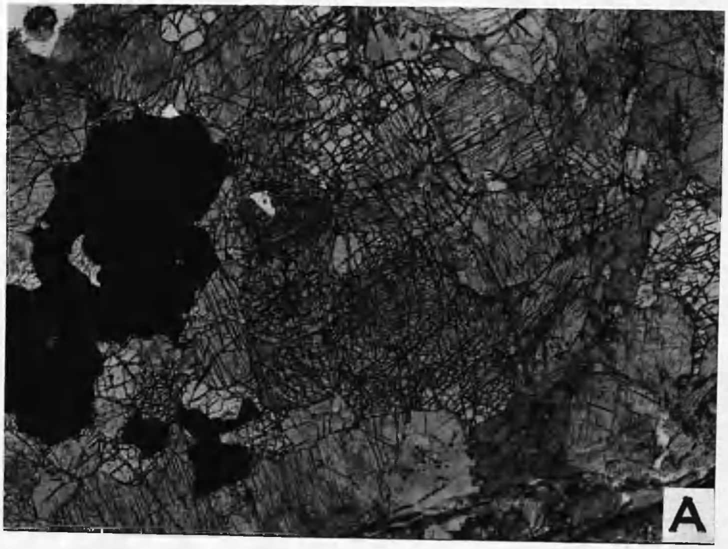
Plate 20: ECLOGITIC ROCKS; KNOCKORMAL

A. Granular aggregates of pyroxene (colourless), amphibole (very pale green) and garnet. The black bodies are crystals of deep green ceylonite.

(OL. x 20)

B. Pyroxene, amphibole and garnet-rock. Some of the garnet forms intergrowths with the amphibole (right centre). A small vein of fibrous prehnite cuts the rock (left centre).

(XN. x 20)


A


B

Plate 21: GRANULITIC ROCKS

A. Granulitized gabbro; Poundland Burn.

Large crystals of diallagic pyroxene undergoing granulation to clear, granular pyroxene. Both the primary and secondary pyroxene are altered to deep brown hornblende. Partially granulitized olivine also occurs (top right) and secondary plagioclase (bottom right).

(OL. x 20)

B. Porphyritic marginal phase of above.

Altered primary plagioclase invaded by secondary pyroxene, plagioclase and hornblende in the ground mass.

(OL. x 20)

C. Granulite; Littleton Hill.

Typical beerbachitic texture defined by granular hornblende and plagioclase. Relict patches of primary plagioclase remain in outline but are partially recrystallised (cf. Plate 22, A).

(OL. x 20)

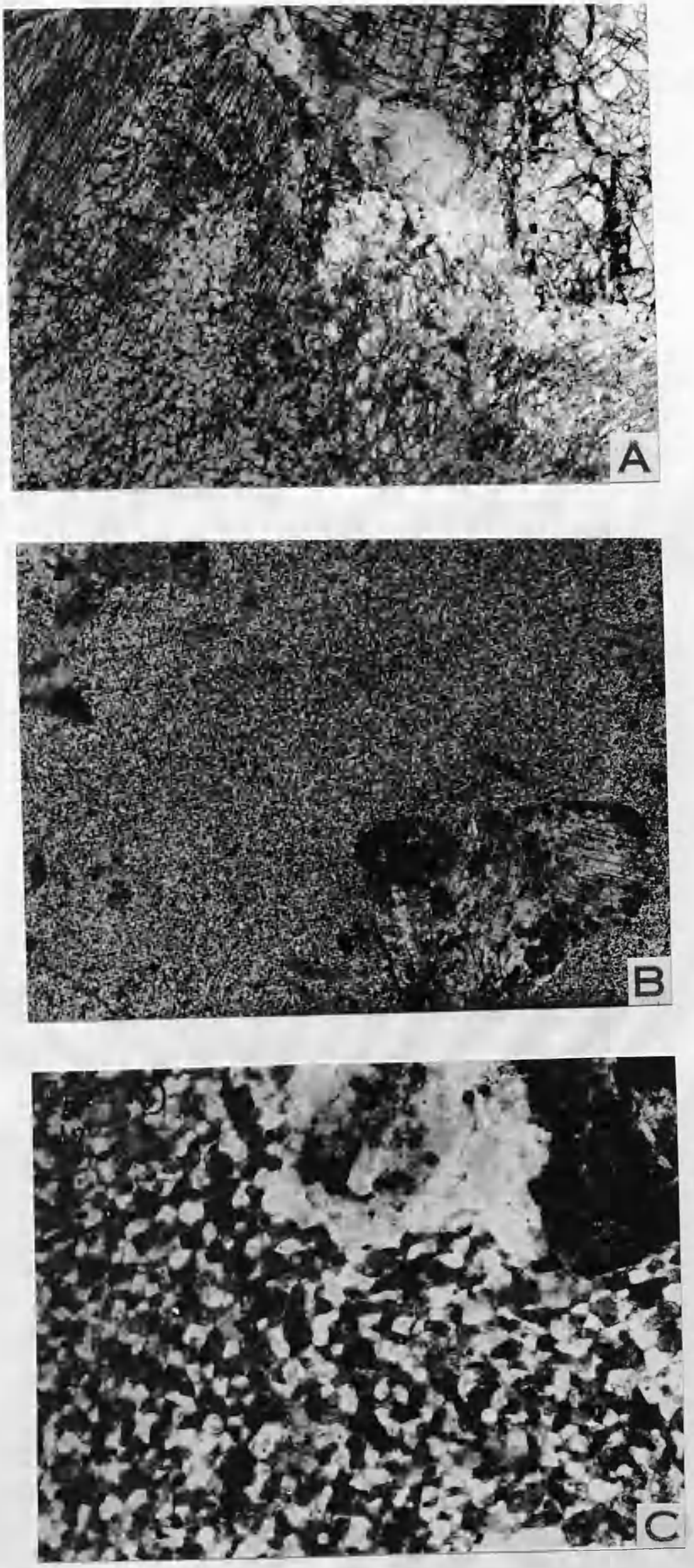

A
B
C

Plate 22: GRANULITIC ROCKS

A. Granulite; Littleton Hill.

Plate 21, C, nicols crossed.

B. Porphyritic granulite; Littleton Hill.

Thermally clouded primary plagioclase crystals are prominent. The groundmass exhibits relict flow banding in recrystallised plagioclase laths. The remainder of the rock consists of deep brown hornblende and occasional biotite. The rock may have been a lava (cf. Plate 11, A).

(OL. x 20)

C. Porphyritic granulite; Littleton Hill.

Note the inclusions of groundmass material in the thermally clouded plagioclase phenochrysts, a structure common in basalts.

(OL. x 20)

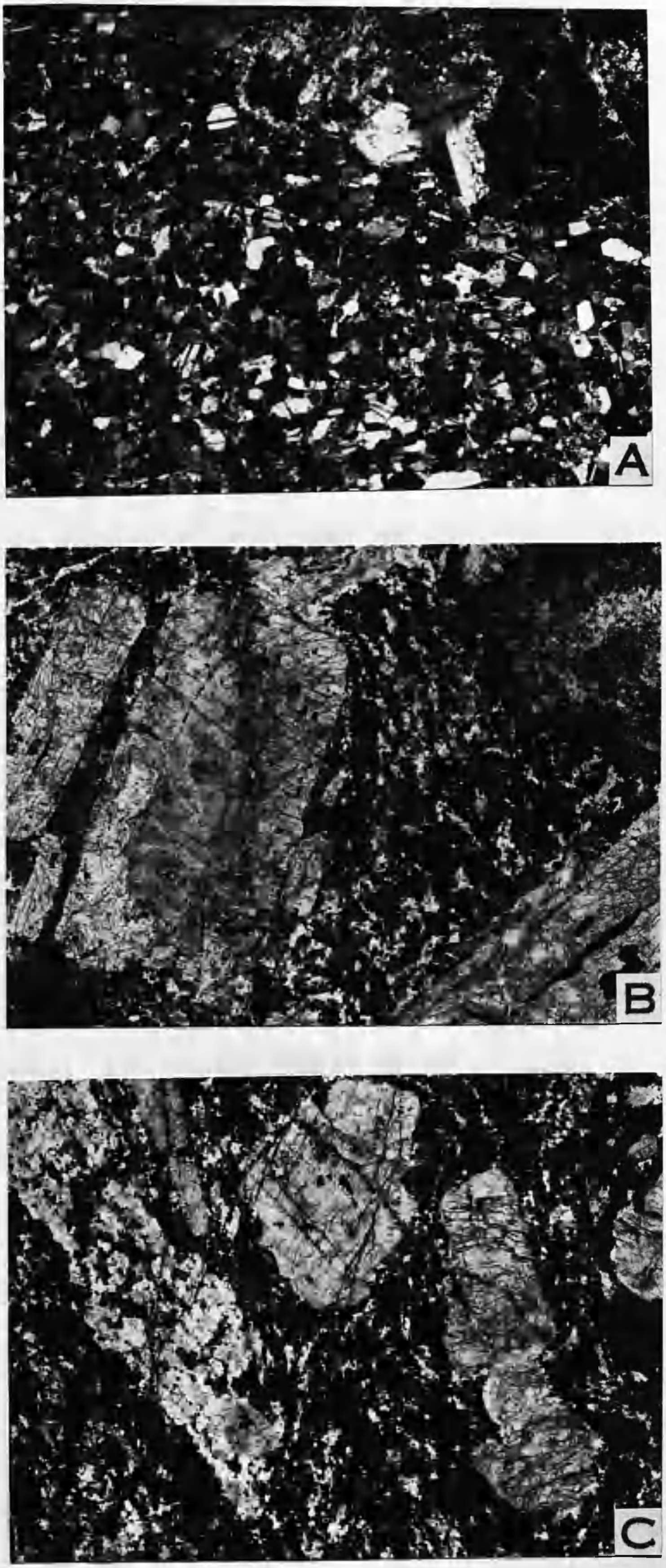

A
B
C

Plate 23: GRANULITIC ROCKS

A. Slightly schistose granulite; Littleton Hill.

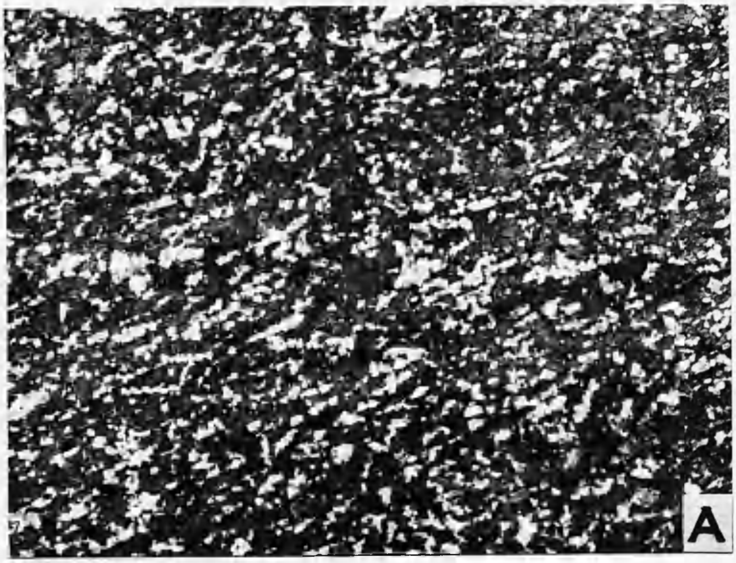
The rock consists mainly of brown hornblende and plagioclase.

(OL. x 20)

B. Banded granulite; Poundland Burn.

Light band of diopside and plagioclase in sharp contact with a dark band of predominantly brown hornblende and plagioclase.

(OL. x 20)


A


B

Plate 24: FLASERED GABBROS AND GRANULITE;

MILLENDERDALE

A. Hand specimen of ophitic central portion of the mass showing hard white saussurite and dark brown hornblende after pyroxene.

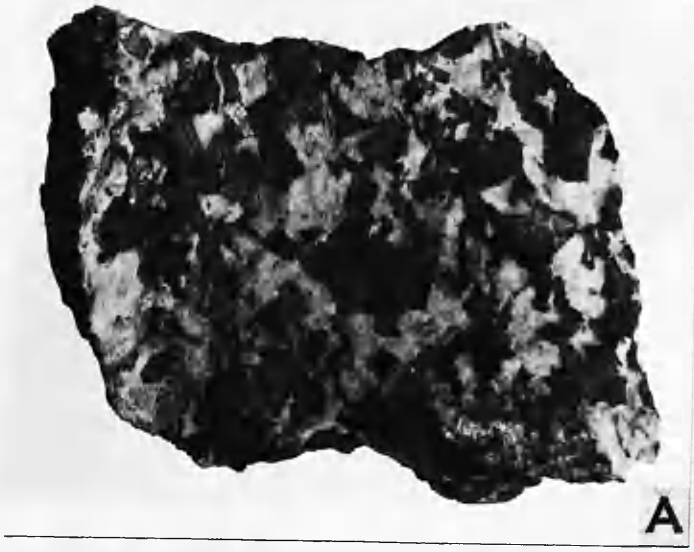
(Approx. full size)

B. Thin section of above. Note the recrystallisation of the diallagic pyroxene, still ophitically related to saussuritized plagioclase (cf. Plate 21, A).

(OL. x 10)

C. Flasered gabbro near the margin of the mass. Note the finer grained bands developing.

(Approx. full size)


A


B


C

Plate 25: FLASERED GABBROS AND GRANULITE; MILLENDERDALE

A. Marginal phase of the gabbro mass.

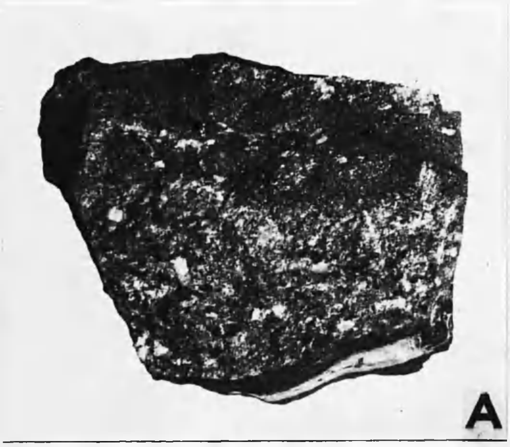
Flasered and sheared bands of coarse gabbro in juxtaposition with finer grained non-schistose granulitic band (top of picture).

(Approx. full size)

B. Thin section of above.

Coarse sheared bands passing quite abruptly into non-schistose granulitic bands. Most of the plagioclase has recrystallized but retains its primary (lenticular) outlines in the coarser bands.

(OL. x 10)


A

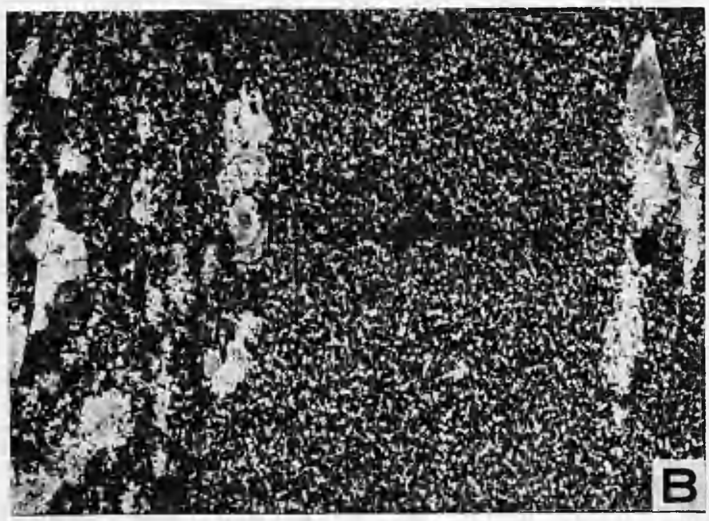

B

Plate 26: DIABASES; CONTACT PHENOMENON;

LENDALFOOT

A. Central portion of large diabase dyke intrusive in ultrabasic rocks (Plate 5, A). The rock is much altered and consists of turbid plagioclase and fresh titan-augite.

(OL. x 20)

B. do., nicols crossed.


A


B

Plate 27: DIABASES; CONTACT PHENOMENON;

LENDALFOOT

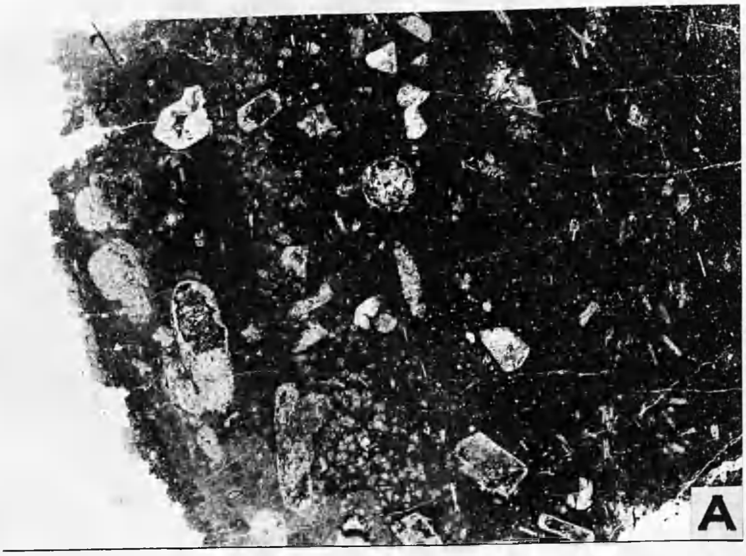
A. Contact of diabase towards serpentinite. The specimen has broken along the actual contact (left) but a very thin serpentinite selvage is just visible. The contact diabase is porphyritic and possesses a glassy mesostasis (cf. Plate 29).

(OL. x 8)

B. Partially serpentinized harzburgite selvage to above. Dense aggregates of granular, closely sutured, olivine; rendered nearly opaque by minute ore. Lighter crystals of partially altered bronzite also occur together with veins of chrysotile.

The rock was probably contact altered prior to serpentinization.

(OL. x 20)


A


B

Plate 28: BYNE HILL GABBRO

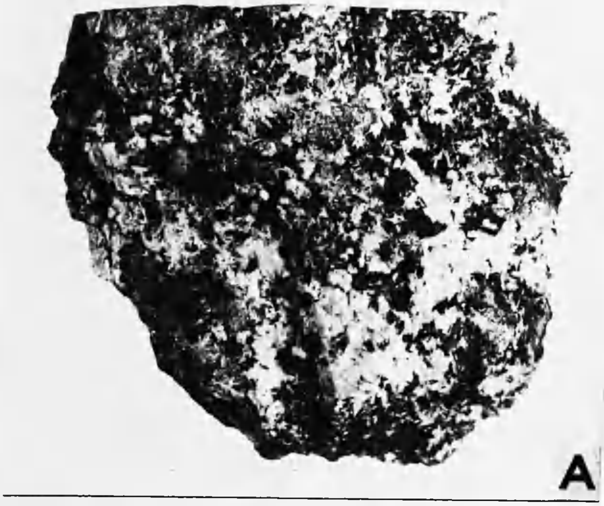
A. Hand specimen showing the variable amounts of plagioclase and dark minerals in the rock. The texture is strongly ophitic but exhibits considerable variations in grain size.

(Approx. full size)

B. Thin section of above.

Turbid plagioclase (saussuritized) and deep brown hornblende after pyroxene are prominant. The hornblende is so strongly coloured that it appears to be almost black in the photograph.

(OL. x 30)



A

B

Plate 29: BYNE HILL GABBRO; CONTACT PHENOMENON

A. Contact (arrowed) between fine grained margin of gabbro and serpentinite.

(OL. x 10)

B. do.

C. do.

Some of the veins carry grossularite in addition to pectolite and prehnite.


A


B


C

Plate 30: BYNE HILL GABBRO; CONTACT PHENOMENON

A. Idealized sketch of the contact shown in Plate 29, C to indicate more clearly the distribution of the zones of alteration.

(Approx. x 30)

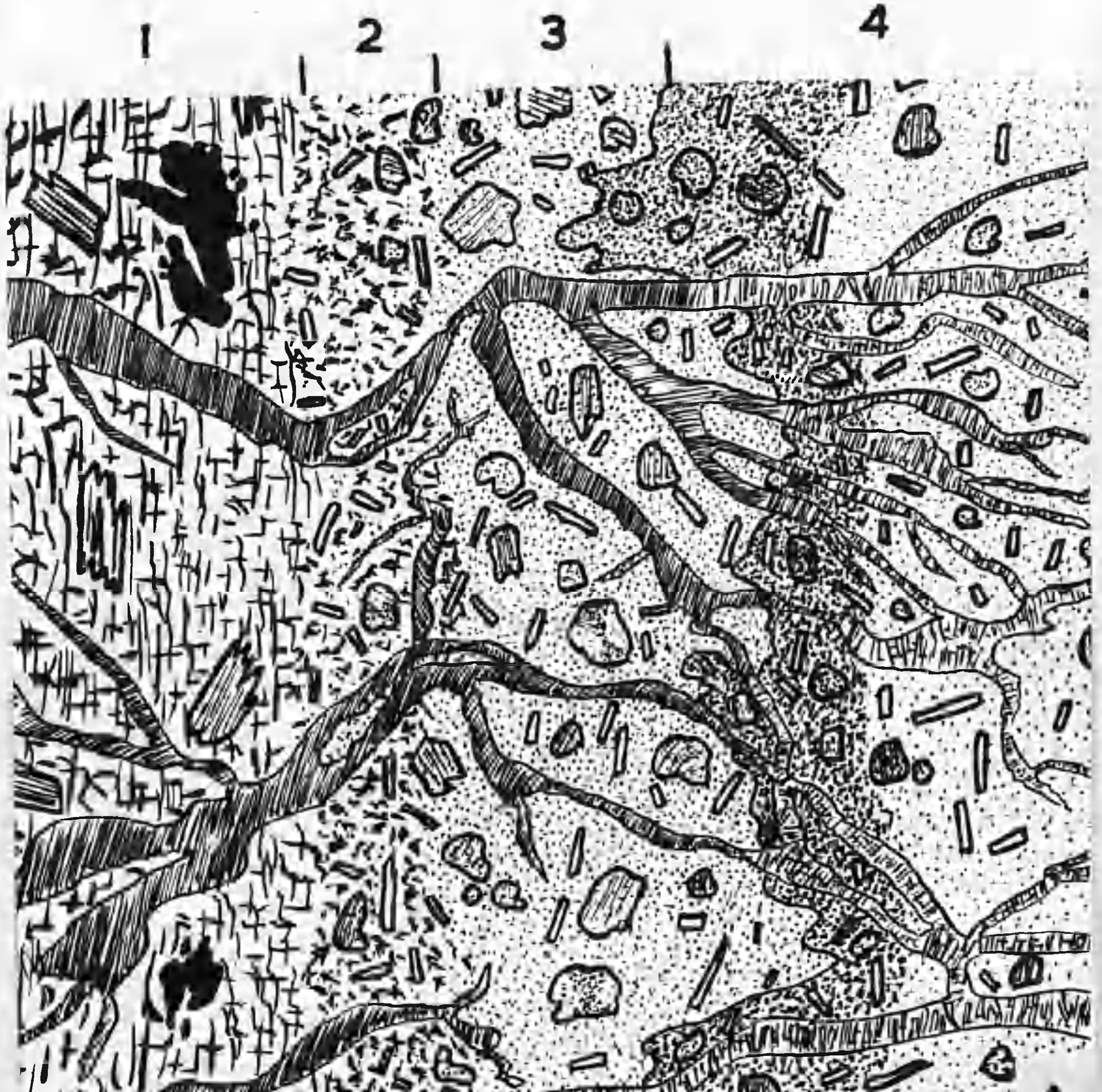

1
2
3
4
A

Plate 31: OTHER GABBROIDAL MASSES;

BURNFOOT AND TROAX

A. Small vein of gabbro (altered felspar, enstatite and olivine) cutting serpentinite; Burnfoot (cf. Plate 9, A).

Dense aggregates of ore are developed in the serpentinite marginal to the basic vein.

(OL. x 4)

B. Even grained ophitic gabbro; Troax.

The rock consists of secondary amphibole and saussuritized plagioclase.

(OL. x 20)


A

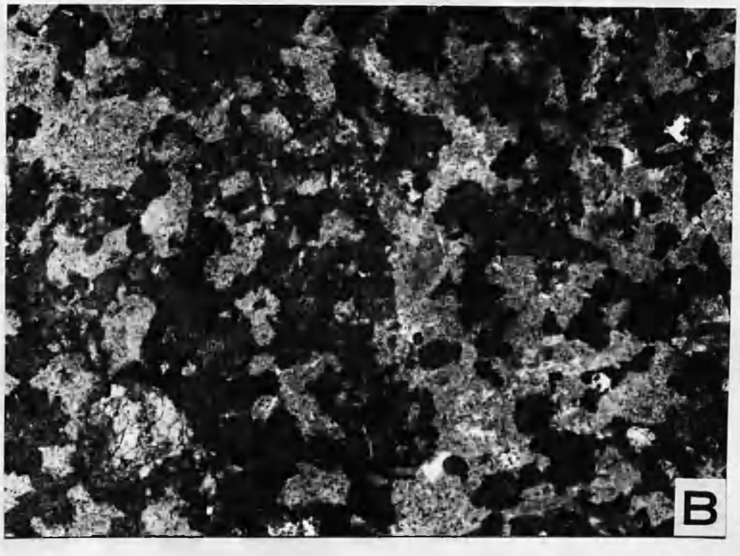

B

Plate 32: (A) OTHER GABBROIDAL MASSES; KNOCKORMAL

(B) ALTERED SERPENTINITE; BYNE HILL

A. Altered gabbro; Knockormal.

Saussuritized plagioclase in ophitic relationship with secondary green hornblende.

(OL. x 30)

B. Contact altered serpentinite marginal to a Tertiary dyke; Byme Hill.

Mesh structure almost obliterated. Large ovoid areas composed of fine grained ore and chlorite. Relict picotite is also present.

(OL. x 6)


A


B

Plate 33: GARNETIZED GABBROS (RODINGITES);

BYNE HILL

A. Completely garnetized plagioclase ophitically related to chloritized pyroxene. A large grain of magnetite occurs near the centre of the field.

(OL. x 20)

B. do., nicols crossed.

The original gabbroidal texture is brought out more clearly. The plagioclase is rendered quite isotropic, but its crystal outlines remain. A large area of chloritized pyroxene is prominent (lower right)

C. Partially garnetized dyke-rock. Veins bearing grossularite and prehnite traverse the rock in which subhedral pyroxene is prominent.

(OL. x 6)

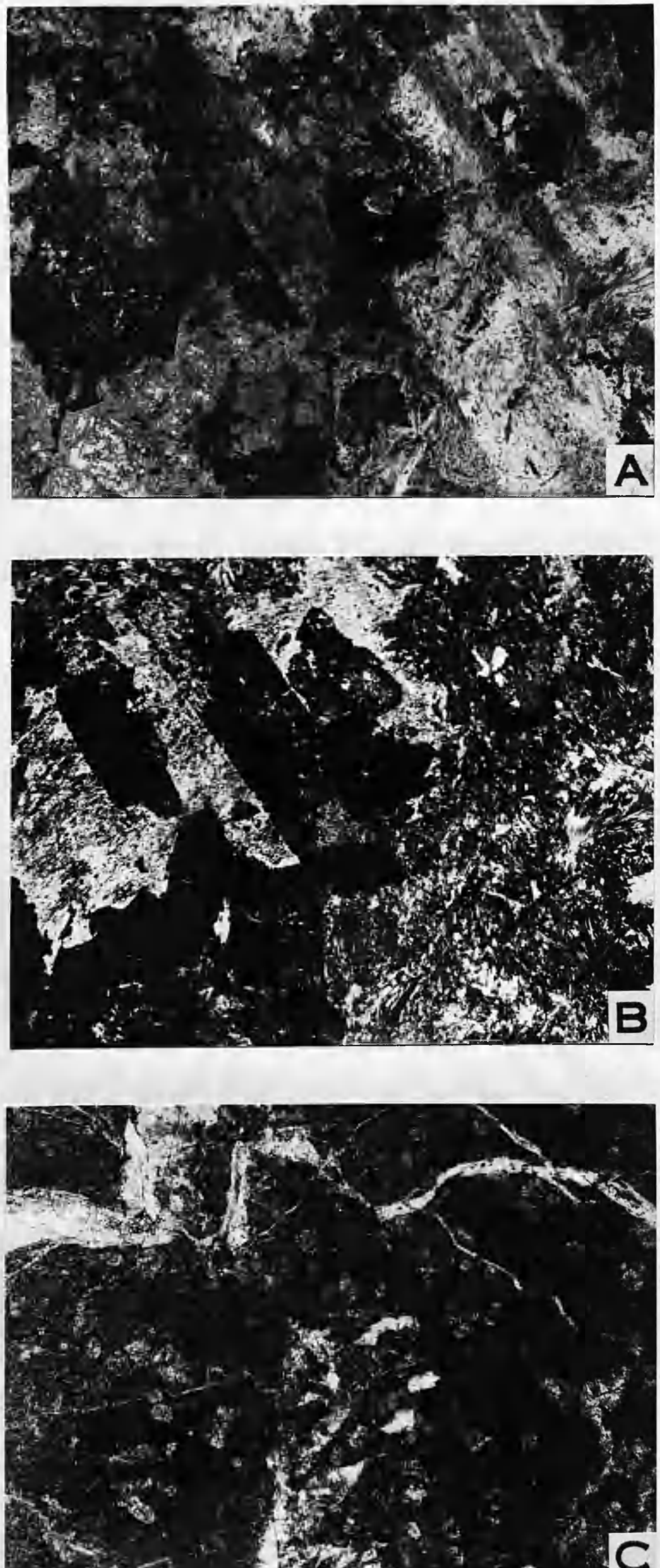

A
B
C

Plate 34: CARBONATED SERPENTINITES

A. Carbonated serpentinite; Moak Hill.

The groundmass and a prominent bastite crystal are replaced by magnesium-iron carbonate. Relict picotite remains intact.

(XN. x 20)

B. Carbonated serpentinite; Byne Hill.

Serpentinite completely replaced by carbonate, only relict picotite remains as a prominent fractured crystal.

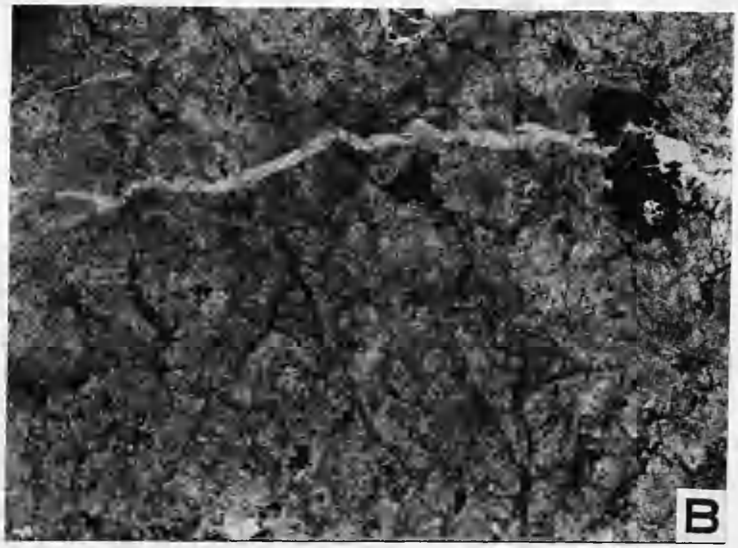
(OL. x 20)

C. Carbonated serpentinite; Knockdhu.

The rock consists almost exclusively of angular carbonates and magnetite.

(OL. x 20)


A


B


C

Plate 35: CARBONATED SERPENTINITE

A. Carbonated serpentinite; Knockdhu.

The texture of serpentinite is preserved but is being replaced and destroyed by aggregates and veins of carbonate.

(XN x 20)

B. Carbonated serpentinite; N. Ballaird.

As above, but small igneous fragments are also present (right).

(OL. x 20)


A


B

Plate 36: BASIC AND ACID INTRUSIVES; BYNE HILL

A. Acidified gabbro. Large clots of amphibole after pyroxene are prominent and the texture is gabbroidal. The rock carries biotite (6 feet from diorite).

(Approx. full size)

B. do.

The rock is more even grained and felspathic with abundant biotite. The texture is still gabbroidal (1 foot from diorite).

(Approx. full size)

C. Thin section of B, above. The rock consists largely of saussuritized felspar and biotitized amphibole.

(OL. x 12)

D. Acidified gabbro. The gabbroidal texture is breaking down to a more xenoblastic granitoid texture leaving coarser gabbroidal clots disposed throughout the rock.

(Approx. full size)

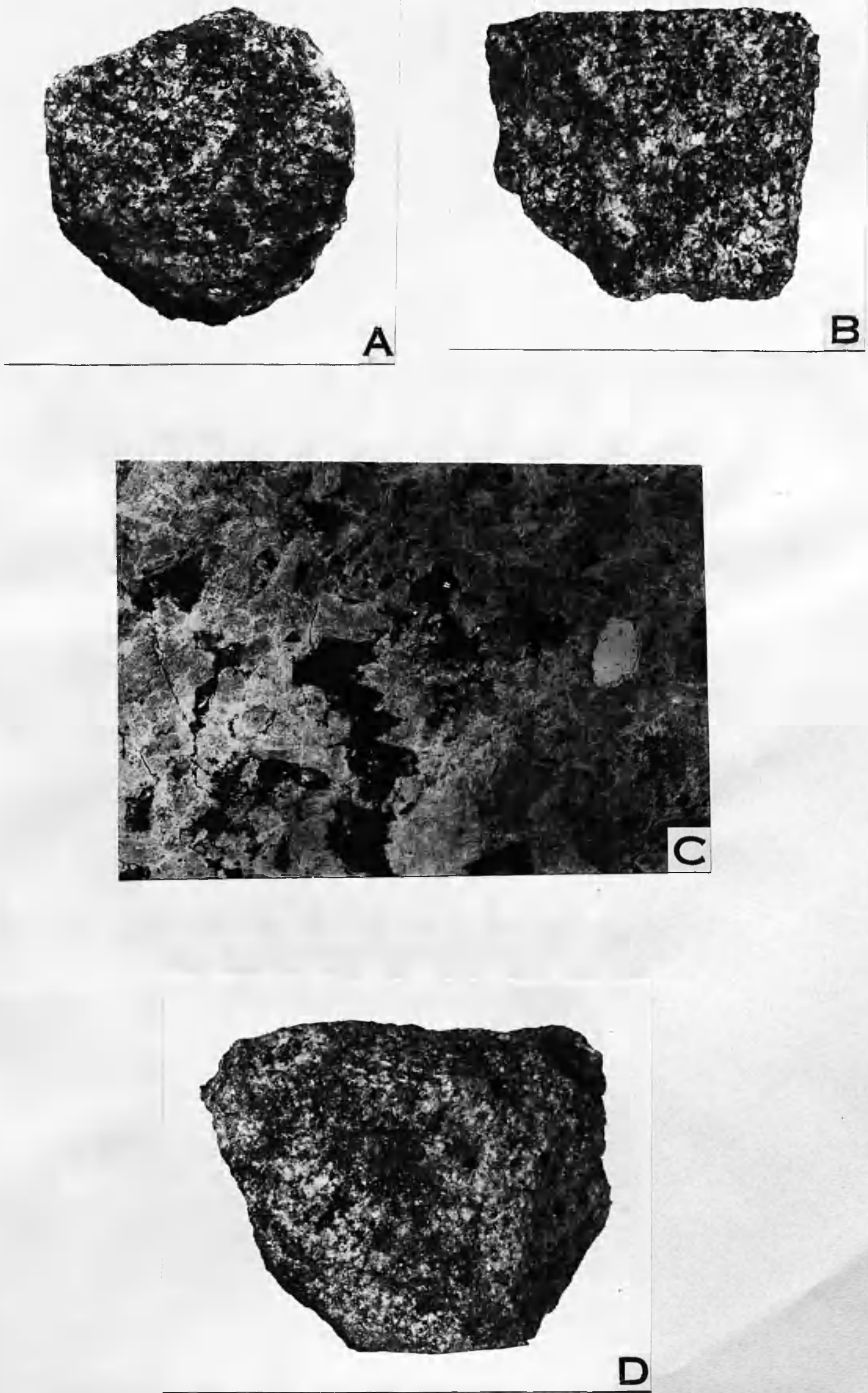

A
B
C
D

Plate 37: BASIC AND ACID INTRUSIVES; BYNE HILL

A. Acidified gabbro. The gabbroidal texture has virtually disappeared although a large clot of hornblende remains. The rock is cut by a pegmatitic vein of quartz, orthoclase and biotite (left).

(Approx. full size)

B. Basified granite (albite-diorite) containing altered hornblende, chlorite and biotite. The plagioclase may be primary in origin.

(OL. x 12)

C. Quartz-diorite or basified granite. Quartz is visible macroscopically.

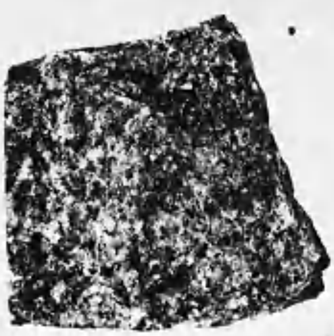
(Approx. full size)

D. Granite.

(Approx. full size)

A

B



C

D

Plate 38: ACID INTRUSIVES; BYNE HILL

A. Granite. The rock consists of euhedral plagioclase albitized and kaolinized with a rather patchy development of anhedral quartz and biotite.

(OL. x 12)

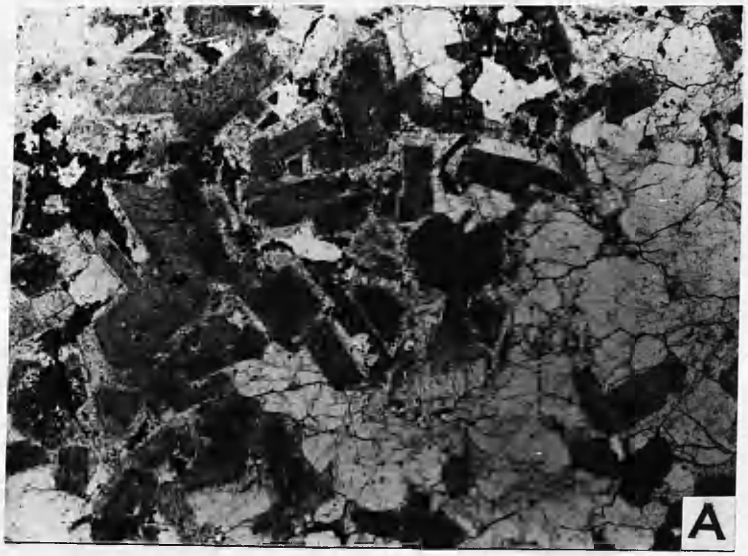
B. Sheared and brecciated granite along fault zone.

(Approx. full size)

C. do.

Thin section showing the thoroughly cataclastic texture of the rock.

(XN. x 12)


A


B

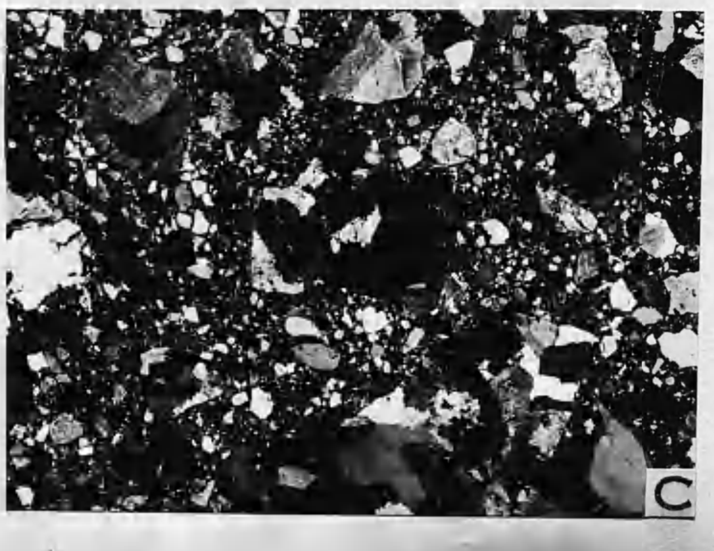

C

PLATE I.


N
RECENT DEPOSITS
PALAEOZOIC SEDIMENTS
SCHISTOSE BASIC ROCKS
GRANITE
YOUNGER BASIC ROCKS
ULTRABASIC ROCKS
OLDER BASIC ROCKS
ARENIG
SPILITIC LAVAS & TUFF
FAULTS
GEOLOGICAL BOUNDARIES WHERE UNCERTAIN
0 1 2 MILES
WOODLAND
ARDWELL
KENNEDY'S PASS
MAINS HILL
BYNE HILL
FELL HILL
GREY HILL
CAIRN HILL
PINBAIN
PINBAIN HILL
BALKEACHY
LOCH LOCHTON
LENDALFOOT
BURNFOOT
CARLETON HILL
LAIGH KNOCKCLAUCH
BENNANE HEAD
TROAX
N.BALLAIRD
KNOCKORMAL
MILLENDERDALE
S BALLAIRD
MOAK HILL
PINMORE
KNOCKDAW HILL
LITTLETON HILL
BREAKER HILL
BALHAMIE HILL
KNOCKDOLIAN HILL
SALLACHAN HILL
COLMONELL
GARNABURN
BALLANTRAE
POUNDLAND
KNOCKDHU
RIVER STINCHAR
RIVER STINCHAR
DOWNAN POINT
PINWHERRY

PLATE 2.


N
Bynehill Cottage
Bynehill Bridge
Girvan 2
Barrhill 10½
M.S
100
200
300
400
500
600
701
Byne Hill
Balcletchie Wood
F.P.
Monument
A
B
BALA
BENAN CONGLOMERATE
ARENIG
GRANITE
BASIFIED GRANITE
DIORITE
GABBRO
SERPENTINITE
RODINGITE
SERPENTINIZED DOLERITE
? TERTIARY
DOLERITE
REVERSE FAULT
do. WHERE UNCERTAIN
OTHER FAULTS
HIGHLY INCLINED
100 0 500 1000 FEET