Sedimentary inclusions in the hypersthene-gabbro, Ardnamurchan, Argyllshire.

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[Read January 11, 1951.]

Introduction.

THE hypersthene-gabbro of Ardnamurchan Point is the earliest of the intrusions of 'Centre 2' of the Ardnamurchan complex as shown by J. E. Richey (11, p. 208).[1] The mass is intruded into domed Jurassic sediments and Tertiary basalt flows (fig. 1). The main part of the intrusion is composed of rather fine-grained gabbro, containing 2–3 % of hypersthene which typically surrounds crystals of olivine. Marginally, however, the gabbro is a quartz-bearing variety, with a micrographic mesostasis. The outer contact is somewhat sinuous due to the fact that the intrusion has only been exposed to a comparatively small depth below its original roof. This same geological accident may account in part for the number of fine-grained, basic, granular masses that are locally abundant within the gabbro. These masses, variously described as pyroxene-granulite or pyroxene-granulite-hornfels, have a granoblastic texture and are composed of normal gabbroic minerals: plagioclase, augite, olivine, hypersthene, and magnetite. They have been described in detail by J. E. Richey and H. H. Thomas (11, pp. 229–235) who considered them to be derived in part from the recrystallization of baked inclusions of basalt, and in part from cognate masses of early emplaced gabbro, prized off the walls and incorporated in the later pulses of the gabbro magma. The only other description of inclusions in the hypersthene-gabbro is that of A. G. MacGregor (6) who compared these pyroxene-granulite-hornfelses with similar rocks of other areas and concluded that they represent basaltic and gabbroic rocks that have suffered thermal, and essentially non-additive, metamorphism. The only previous mention of sedimentary rocks in the gabbro is in connexion with the sapphire-spinel-hornfels that occurs at the northern end of Glebe Hill, near Kilchoan (locality 5, fig. 1), and which Thomas believed

[1] For list of references see p. 735.

to be derived from an aluminous bole produced by weathering of Tertiary lavas (11, pp. 233–235).

The published accounts lead one to suppose, therefore, that sedimentary inclusions are virtually absent from the hypersthene-gabbro.

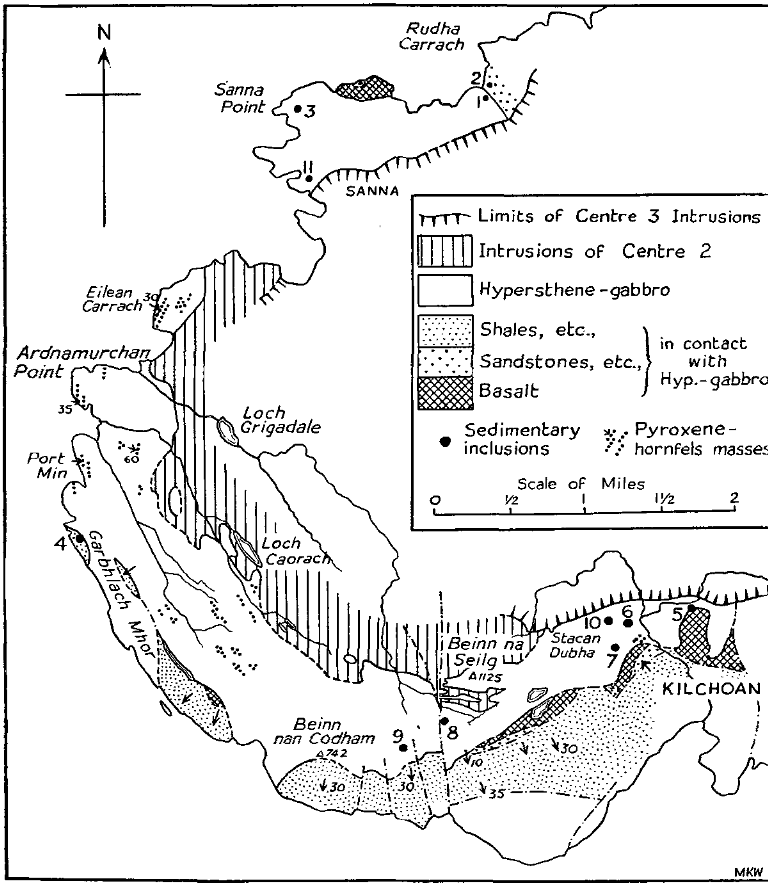

FIG. 1. Map showing localities of xenoliths in the hypersthene-gabbro. (The main boundaries have been taken from the coloured map of the Ardnamurchan memoir, 1930.)

In actual fact, xenoliths that one would class unhesitatingly as of sedimentary origin are exceedingly rare, and the writer has discovered only three occurrences (or four with the sapphire-bearing rocks already known); but there are, in addition, a number of banded granulite-hornfelses whose origin may be considered doubtful, but which are most probably derived from sediments. They have been chemically reconstituted, and evidence regarding their origin rests largely upon their microtexture, and upon structures which are believed to be inherited. Even if this view is taken, the number of probable sedimentary inclusions is still greatly outweighed by that of inclusions of igneous appearance, and the dominance of the latter, is an intrusion emplaced largely amongst sediments, remains a major problem.

The writer proposes to describe first the few xenoliths whose sedimentary origin is not in doubt, and to follow this by a discussion of the origin of the more abundant banded or layered basic hornfelses which he believes to be sedimentogenous also. The xenoliths in the first category are in all cases surrounded by marked reaction zones. In the order in which they are described these xenoliths are: (1) siliceous rocks which have been felspathized to produce granophyre: (2) finely interbedded shaly and ferruginous rocks which have been converted to rocks of noritic composition; and (3) peraluminous sediments (bole) which have been altered to basic plagioclase-magnetite-spinel-(corundum)-rocks.

Siliceous xenoliths and their reaction with gabbro magma.[1]

The hypersthene-gabbro intrusion terminates with a steep junction against the Scalpa beds (Middle Lias) at the north-western end of its outcrop. These beds are chiefly fine-grained sandstones with subordinate shaly and calcareous layers. They are cut by numerous cone-sheets and a few small dikes, the whole assemblage being metamorphosed by the hypersthene-gabbro. Two rounded inclusions of profoundly altered sandstone, both about a foot in diameter, occur about 15 feet inside the gabbro just above high-water mark (loc. 1, fig. 1). Unfortunately this otherwise ideal exposure is marred by a black oily coating close to the sea and some of the finer points of the geology may easily be overlooked. These two xenoliths are conspicuous, however, for they have been recessed by weathering and have developed a fretted surface. Each inclusion has two parts; a very fine-textured core of light rock, speckled with coloured minerals sparsely scattered through it, and a complex marginal zone showing small-scale banding and dense concentrations of

[1] Since a number of the effects described in this paper are metasomatic, it is advisable to state that the gabbro as a whole shows evidence of a magmatic origin. This evidence will be given in a forthcoming account of the petrology and structure of the hypersthene-gabbro and adjacent intrusions.

coloured minerals (fig. 4). The mineral content and texture changes rapidly within the marginal zone so that it is possible to distinguish an inner and an outer part as described below, despite the fact that the total width is only about an inch.

The cores of the xenoliths consist dominantly of micrographic intergrowths of quartz and alkali-felspar, with aggregated crystals of green clinopyroxene. The latter is a pale mineral with the following optical properties: β 1·722$\pm$0·002 2V 63°$\pm$1°, $\gamma:c$ = 55°. The pleochroism scheme is α yellowish-green, β yellow-brown, and γ bluish-green. These properties correspond most closely with those which Winchell (15, p. 191) gives for a pyroxene of the diopside-hedenbergite series with a small content of acmite, approximately $Di_{40}Hd_{50}Ac_{10}$. The crystals are ragged in outline and have a maximum diameter of about 1 mm. Plagioclase is subordinate to the micrographic alkali-felspar, and occurs as isolated well-formed grains showing quite strong zoning. The more calcic parts of these crystals are clouded with minute iron-ore inclusions in a manner that is characteristic of the plagioclase of all the surrounding gabbro. This is probably a thermal metamorphic effect due to the nearby great eucrite intrusion of 'Centre 3'. Sphene and apatite are the only other important constituents. Some of the sphene crystals are perfectly euhedral but others are completely shapeless. The apatite occurs as euhedral bluish prismatic crystals up to about 0·25 mm. in length, having clouded cores. Occasional patches of calcite can be observed, interstitial to well-formed quartz.

In one specimen, the granophyric core of the xenolith passes abruptly into the complex marginal zone, which is in two parts. The inner part consists of spongy porphyroblasts of the green pyroxene and sphene set in a groundmass of minutely granular plagioclase. The latter occurs as equant grains of almost square cross-section, which are feebly twinned and marginally zoned. Accurate refractive index measurements on the central and marginal parts of such minute crystals are difficult to make; but the zoning appears to be normal, involving a small range of composition, with a maximum anorthite content of 40. The coloured minerals are concentrated into well-marked bands. In view of the weathered-in nature of the xenoliths, it is impossible to say whether this development of unusually large quantities of sphene and of plagioclase is present all round both xenoliths, or whether it is a purely local development, dependent upon the presence of more lime than usual in one part of the original rock. Although the calcium may have been derived in part from the parent rock, the titanium cannot be accounted for in this way, and its presence affords a good example of a geochemical culmination of a single element which is not otherwise abundant, either in the gabbro or in the xenolith rock.

The remaining outer part of the marginal zone of both xenoliths consists solely of the green pyroxene. A similar narrow zone of pyroxenite is also found at the main contact which the gabbro makes with the sediments. As one passes across the pyroxenite away from the xenoliths or the main mass of sediments and into the gabbro the pyroxene loses its colour, and half-an-inch from the margins of the xenoliths all that remains is a feeble marginal green zoning around the normal colourless gabbroic augite. Beyond that the hypersthene-gabbro assumes those characteristics which are found with little variation in all the marginal facies of the intrusion. The most notable feature is the occurrence of quartz in a micrographic mesostasis, as already mentioned. The plagioclase is lath-shaped and frequently intergrown with ophitic augite. Although this quartz-gabbro is part of the so-called hypersthene-gabbro intrusion, the marginal facies are very deficient in the hypersthene. Since the petrology of the gabbro is going to be described fully in a later account, no further details will be given here.

Clear evidence bearing on the true nature of the granophyre which forms the cores of the xenoliths is afforded by a curious 'breccia' lying a few yards outside the gabbro boundary at Rudha Carrach (loc. 2, fig. 1). This rock consists of very pale angular fragments set in a uniform, finely crystalline matrix. The fragments measure from a fraction of an inch to two inches in diameter. They are composed of recrystallized sutured quartz grains, which are penetrated by irregular veinlets of cryptocrystalline felspar and quartz. The quartzo-felspathic patches swell out in places without disrupting the surrounding quartz aggregate, and it is evident from this and from the increase in the amount of the felspathized material towards the margins of the angular fragments, that this is a case of metasomatism of a highly siliceous rock. The original rock was a sandstone with, probably, a small amount of calcareous cement, as suggested by the calcite in the norm of the granophyre (table I) and by the occasional patches of calcite which occur in the xenoliths. There is also a very small amount of prehnite present in the latter.

An intimate and rather irregular intergrowth of quartz and felspar occurs at the margins of some of the sedimentary quartz grains, and occasionally the latter are in optical continuity with the lace-like development of quartz in the surrounding intergrowths. Generally, however, the quartz intergrown with the felspar occurs as minute lath-shaped crystals of random orientation set in a matrix of cryptocrystalline turbid felspar. These may well be pseudomorphous after tridymite, and in that case they indicate that the felspathization occurred at a high temperature, probably well above 800° C. The general appearance of the rock is very similar to that of felspathic Torridonian sandstone which has been metamorphosed in contact with an ultrabasic intrusion on the island of Rhum, and which Harker describes as reproducing 'all the features of granophyre and quartz-porphyry', except in regard to

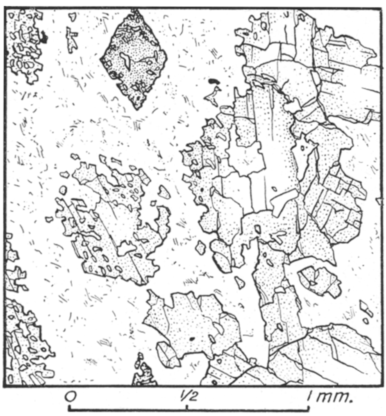

FIG. 2

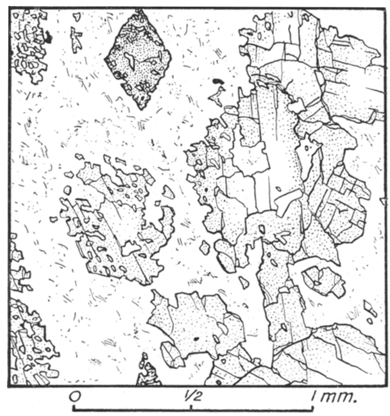

FIG. 3

FIG. 2. Marginal zone of granophyric xenolith, Rudha Carrach (locality 1), showing poikiloblastic crystals of sphene and zoned green pyroxene in a fine-grained groundmass of plagioclase.

FIG. 3. Felspathized sandstone, Rudha Carrach (locality 2).

the preponderance of quartz over felspar (4, pp. 68-69, and fig. 21A). The Rhum and Ardnamurchan rocks differ in one important respect: the felspar in the altered Torridonian is believed to be entirely original, while in the Rudha Carrack rock it is apparently all derived with the aid of metasomatism. The texture produced initially by the felspathization is not truly granophyric for the irregular quartz-felspar intergrowths are not geometrically perfect, as they are in the true granophyre found immediately adjacent to the hypersthene-gabbro and in the xenoliths. Small felspar crystals showing albite twinning occur together with the turbid (presumably alkali) felspar intergrown with the quartz in the breccia. The only other minerals present in this rock are minute scales of dark green chlorite, some iron ore, and needles of apatite.

Mobilization of the Rudha Carrach 'granophyre' is shown by the breaking-up and movement of the angular quartz fragments in the breccia. A chloritic streakiness wraps around some of these fragments like flow lines around the phenocrysts in a lava. Such mobilization seems to be a normal sequence to felspathization: it is shown by granophyre veinlets emanating from siliceous xenoliths which have been felspathized in contact with lamprophyres in dikes in the Ards peninsula of Northern Ireland, and by syenitic veins occurring in hornblendite on the coast of Colonsay, Scotland, both described by D. L. Reynolds (9, pp. 367–407; 10, pp. 51–76); while Walker and Poldervaart (14, p. 614) have described several cases where sedimentary inclusions in the Karroo dolerites have been felspathized and rendered intrusive. The ease with which this mobility is achieved may be due to the attainment of a near-eutectic composition as a result of the metasomatism. This would account not only for the fluidity, but also for the ultimate production of a 'micrographic' texture, for it is possible that the latter can only be produced with any degree of perfection at the threshold of melting of the quartz-felspar mixture. The chemical aspects of felspathization of highly siliceous rocks have been fully described by D. L. Reynolds (loc. cit.). The rock sample from Rudha Carrach selected for analysis (table I, A) contains some of the unaltered quartz of the sandstone, so that direct comparison with other true granophyres is difficult to make. The analysis of a felspathic rim of a quartz xenolith from one of the basic dikes of the Ards peninsula, formed in somewhat similar circumstances to the Ardnamurchan rock, is quoted for comparison.

A diagrammatic summary of the complete sequence of metasomatic effects seen in the xenoliths and at the gabbro contact near Rudha Carrach is shown in fig. 4. It is based upon the assumption (which cannot be verified) that the original sandstone was homogeneous and composed wholly of quartz.

Sedimentary xenoliths in contaminated norite.

A few small pale inclusions of sedimentary origin, with fine laminae etched out by weathering, occur in gabbro which is locally rather felspathic and variable in appearance, near the extremity of Sanna Point (loc. 3, fig 1). The xenoliths are composed largely of basic andesine as strongly zoned minute crystals with a square cross-section, and xenoliths are surrounded by an ultramafic rim an inch or so wide, rich in

TABLE I. Chemical analysis of felspathized sandstone.

	A.	B.
SiO_2	70·78	70·45
Al_2O_3	11·46	13·14
Fe_2O_3	1·14	1·03
FeO	4·63	0·71
MgO	1·27	1·29
CaO	3·06	2·58
Na_2O	2·21	4·47
K_2O	2·85	3·65
H_2O+	0·98	1·30
H_2O-	0·20	0·34
CO_2	0·39	--
TiO_2	0·92	0·57
P_2O_5	0·15	trace
S	n.d.	0·17
MnO	0·17	0·31
	100·21	100·01

Norm of A.		
Quartz		32·10
Orthoclase		17·24
Albite		18·34
Anorthite		13·07
Diopside		1·26
Hypersthene*		
$MgSiO_3$	4·20	10·01
$FeSiO_3$	5·81	
Ilmenite		1·67
Magnetite		1·62
Apatite		1·01
Calcite		0·90

* This represents chlorite in the mode.

A. Felspathized sandstone, Rudha Carrach (loc. 2), Ardnamurchan. Analyst, W. H. Herdsman.

B. Felspathic rim of quartz xenolith in the Kircubbin dike, Ards peninsula. Analyst, E. Kroupa (Reynolds, 1938).

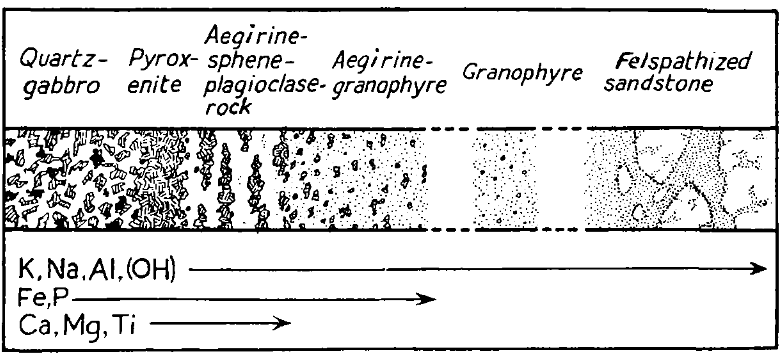

FIG. 4. Composite diagram to show the effects of metasomatism at the contact of gabbro and sediments, Rudha Carrach. The left-hand side of the diagram relates to the xenoliths (see text) and the right-hand side to rocks outside the gabbro contact. The limits of diffusion indicated by the arrows are qualitative only.

hypersthene, followed by two or three feet of norite[1] which grades outwards into the normal gabbro.

In one of the xenoliths, traces of the original bedding are shown by layers of small hypersthene and magnetite crystals, and occasionally by

[1] That is, using the definition of norite as a plagioclase-pyroxene-rock in which hypersthene exceeds clinopyroxene in amount.

lenticles of more coarsely crystalline plagioclase (the unstippled layers shown in fig. 5). Occasionally the smaller plagioclase grains are enclosed in poikilitic patches of quartz. The most prominent bedding feature is the ferruginous layer shown in fig. 5. This must have provided an easy path for the metasomatizing agents, for the densely concentrated magnetite grains are enclosed in large crystals of hypersthene, mica, and plagioclase.

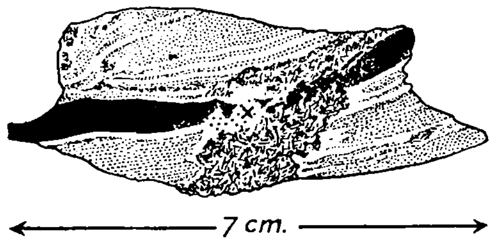

Fig. 5. Drawing of polished surface of xenolithic fragment, showing lamination parallel to a prominent layer of recrystallized iron ore, which is invaded but not displaced, by a tongue of mica-hypersthenite. x marks the position of the thin section drawn in fig. 6. Sanna Point.

The ultramafic zone is composed of hypersthene ($En_{65}Fs_{35}$), dark mica, and iron ore, with subordinate interstitial patches of quartz having straight boundaries. As shown in fig. 5 a lobe of this mica-hypersthenite threads its way across the bedding planes apparently without disrupting them, and, when it breaks through the ferruginous layer, the magnetite of the latter remains in place as large irregular grains in the hypersthenite, and in clusters of enlarged rounded grains concentrated in the cores of plagioclase crystals (fig. 6). The latter form part of a very narrow felspathic rim which sheathes the hypersthenite, as shown in fig. 5.

The norite which encloses the xenoliths is a text-book example of this rock-type, as seen from the mode given in table II. Texturally it has most of the features of a rather fine-grained gabbro, except that the sub-ophitic hypersthene crystals are abnormally prismatic (fig. 7), and the small amounts of mica present frequently surround grains of ore as ragged coronas. Only its field association, surrounding the xenoliths, confirms that this almost ideal orthonorite is a product of contamination of the gabbro magma. An analysis of this rock, together with its mode, is given in table II. It compares fairly closely with that of a quartz-norite from the Haddo House district, Aberdeenshire.

The only other rock of truly noritic composition so far discovered in the hypersthene-gabbro occurs as angular blocks scattered within a small area on the north-facing slope of Stacan Dubha (loc. 10). This is a pale, fine-grained felspathic rock, with the hypersthene concentrated into irregular blebs and lenticles, resembling the structure shown in the lower part of the exposure illustrated in fig. 9. Mineralogically this rock has many features which link it with the Sanna Point xenoliths; there is a similar development of minute equant plagioclase grains, with occasional porphyroblasts showing parallel sides but

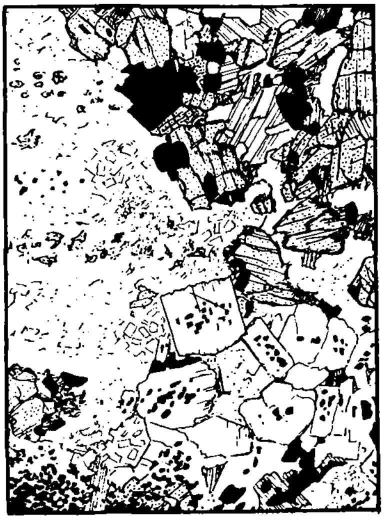

FIG. 6 FIG. 7

FIG. 6. Part of sedimentary xenolith from locality 3, Sanna Point. The minerals shown are plagioclase (as small grains on the left of the diagram, and as porphyroblasts, bottom right, with magnetite inclusions and ragged terminations); hypersthene (stippled); mica showing cleavage; quartz intergrown with the mica of the top right corner; magnetite both as small grains in the ironstone layer (bottom left) and recrystallized patches in the hypersthenite.

FIG. 7. Quartz-mica-norite from the same locality as fig. 6.

irregular lobate terminations; and quartz occurs in small poikilitic patches in both rocks. The most striking feature of the Stacan Dubha rock is the development of sieve-textured prophyroblasts of hypersthene as shown in fig. 8. All of the hypersthenes occurring in the hornfels and contaminated rocks associated with the hypersthene-gabbro have been found to be more strongly pleochroic, and to have a larger optic axial angle than their gabbroic counterparts. In other words, the hypersthene produced under metamorphic conditions appears to be consistently richer in the ferrosilite component than that produced under magmatic conditions.

The sedimentary origin of the Sanna Point xenoliths with their altered

TABLE II. Chemical analysis of quartz-norite.

	A.	B.
SiO_2	54·02	53·80
Al_2O_3	17·51	15·36
Fe_2O_3	1·14	1·07
FeO	6·30	10·67
MgO	6·73	4·91
CaO	8·42	7·02
Na_2O	3·18	2·50
K_2O	0·19	1·03
H_2O+	1·08	0·60
H_2O-	0·39	0·10
CO_2	nil	n.d.
TiO_2	0·58	2·60
P_2O_5	0·04	trace
S	n.d.	0·15
MnO	0·27	0·25
	99·85	100·06

Norm of A.

Quartz		3·96
Orthoclase		1·11
Albite		27·25
Anorthite		28·30
Diopside:		
$CaSiO_3$	2·20	5·65
$MgSiO_3$	2·00	
$FeSiO_3$	1·45	
Hypersthene:		
$MgSiO_3$	14·80	23·78
$FeSiO_3$	8·98	
Ilmenite		1·22
Magnetite		1·62
Apatite		0·34

Mode of A.

Quartz	7·29
Plagioclase (An_{47})	59·20
Augite	4·62
Hypersthene (En_{65})	25·50
Biotite	1·32
Ore	2·07

A. Quartz-norite, Sanna Point (loc. 3) Ardnamurchan. Analyst, W. H. Herdsman.

B. Quartz-biotite-norite, Quitquox, half a mile north-west of Airdlin Methlick, Aberdeenshire. Analyst, W. H. Herdsman. (H. H. Read, 8, p. 609.)

ironstone layers cannot be questioned, and no one studying the structures of the Stacan Dubha rock could doubt that it also has a similar origin. The problem of these felspathic noritic rocks is the same as that which confronted H. H. Read in the case of xenoliths in the Haddo House norite of Aberdeenshire. Read (8, p. 629) concluded that the chances were strongly against the incorporation of country-rock of exactly the right composition to yield 'micronorite' with hypersthene identical with that found in the enclosing norite, unless some metasomatism had taken place. If one assumes that the original sediments were pelitic, then the transfer necessary to bring the mineral phases of the xenoliths into equilibrium with the magma would involve the addition of Ca and Mg, and the reversal of the original K:Na ratio in the country-rock.

Aluminous hornfelses of sedimentary origin.

Hornfelses rich in aluminium and ferric iron are rare in the hypersthene-gabbro, but they merit attention since they include the famous corundum (sapphire)-hercynite-magnetite-hornfels of Glebe Hill, described in detail by Richey and Thomas (11, pp. 233–235). A second small group of xenoliths rich in spinel and magnetite, but without visible corundum, has been found by the writer at the base of Stacan Dubha (loc. 5, fig. 1). The chief interest in this new occurrence lies in the structure of the rock, which is well laminated in places, with the ore and

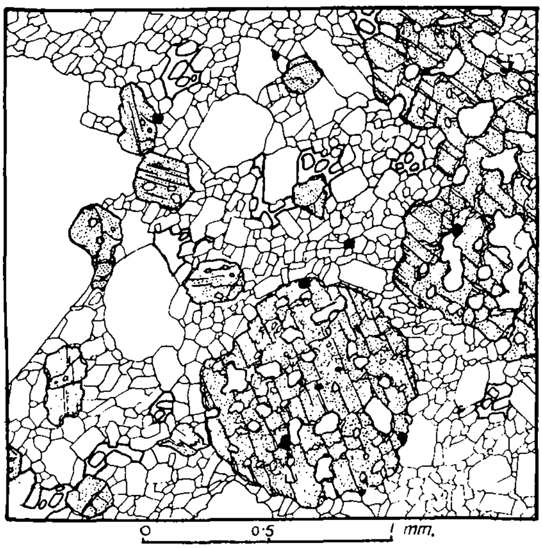

FIG. 8. Hypersthene-plagioclase-hornfels found as scattered blocks on Stacan Dubha (locality 10). The minute plagioclase crystals display the same texture as that found in other xenoliths, e.g. forming the groundmass of the rocks drawn in figs. 2 and 6. Poikilitic patches of quartz are heavily outlined.

spinel laminae projecting, and the intervening plagioclase bands recessed on the weathered surface. Sometimes the structure is more cellular, with a very complete segregation of the dark minerals. This can only be a replacement structure inherited from a well-laminated deposit, and it rules out any suggestion of an igneous origin. Structurally the Glebe Hill hornfels is similar to, though it is more irregular than, the Stacan Dubha example, in respect of the segregation of the light and dark components.

Under the microscope the hercynite in these hornfelses is almost opaque, only the smallest octahedra and the edges of the larger grains showing the deep green colour. The magnetite and hercynite are either densely concentrated to form quite opaque aggregates of irregularly intergrown crystals, or are enclosed in plagioclase which is normally finely granular; but where the opaque minerals are less abundant, the plagioclase occurs as larger crystals, the cores of which are clouded by myriads of exceedingly minute, rod-like inclusions of ore. The plagioclase is labradorite, and is therefore not exceptionally aluminous. The growth of the spinel has affected the adjacent plagioclase in places, giving a narrow shell of felspar of different composition from the average, so that when the plagioclases are in the position of mean extinction, a narrow bright zone surrounds each spinel crystal. Some of the larger spinels act as nuclei for a radial growth of minute felspar crystals. These rocks, then, have unusual composition and structure, and from their very abnormality it should be possible to arrive at a conclusion regarding their origin. The choice seems to lie between two alternatives. In the first place the concentration of aluminium and ferric iron suggests derivation from a residual weathered deposit, such as a 'bole' as suggested by H. H. Thomas (11, p. 235). In that case one has to account for the presence of Si in all the minerals except the magnetite and sparse corundum, of Ca and Na in the plagioclase, and of Mg in the spinel. As an alternative, one may regard these peraluminous hornfelses as the products of sedimentary rocks, originally moderately aluminous, to which Al has been added from the magma. This is the hypothesis favoured by H. H. Read (7, p. 453). The Ardnamurchan hornfelses provide little fresh evidence towards the solution of this problem. All that one can say with certainty is that the hornfelses have structures of sedimentary type, and that, whichever of the above hypotheses is the correct one, it seems inevitable that some reaction has taken place between the xenoliths and the magma.

Basic granular hornfelses.

The most abundant inclusions in the hypersthene-gabbro are rocks composed of the normal gabbroic suite of minerals and having a granoblastic texture. There is at present no satisfactory comprehensive term which can be used to describe all these rocks. In the past they have been referred to as pyroxene-granulites by Harker (3, p. 115); as gabbro-(or basalt-, &c.)granoblasts by Schwartz (13, p. 117); and as pyroxene-granulite-hornfelses by A. G. MacGregor (6). Other terms such as beerbachite and gabbro-aplite have been used to describe similar rocks having either a real or deceptive intrusive appearance in the field (Chelius, 1, p. 4). Objections can be raised to all of these terms on one or other of the following grounds:

(*a*) The parent rocks of many of these inclusions are unknown and can only be inferred. This point is clearly brought out by the use of an analysis of one of these rocks occurring in the Duluth gabbro, in two quite different contexts: firstly, by G. M. Schwartz (13, p. 120) as an indication of the negligible chemical change undergone by basalt in the process of granulitization; and secondly, by F. F. Grout (2, pp. 675–694, anal. no. 13) to illustrate the drastic chemical alteration undergone by slates under the same conditions. Hence the terms gabbro-, or basalt-granoblast are inadmissible except where the origin can be proved beyond doubt.

(*b*) The word 'granulite' without qualification, has been applied to a special kind of quartzo-felspathic tectonite, and its wider use is open to criticism. The present rocks are non-tectonites.

(*c*) Not all of these rocks contain pyroxene; olivine, for example, is dominant in many of them.

The comprehensive term 'basic granular hornfels' is therefore suggested, and for greater precision in any particular case, the leading minerals present may be noted, thus: granular hypersthene-plagioclase-hornfels. The nomenclature of these rocks would then be on the same footing as that of other metamorphic rocks, such as garnet-mica-schist or andalusite-cordierite-hornfels.

In the hypersthene-gabbro these rocks fall into two categories: (1) pyroxene-rich hornfelses with no marked structural characteristics, and (2) layered hornfelses often deficient in clinopyroxene, but containing olivine and hypersthene in abundance. Their distribution is shown in fig. 1, and it should be noted that the layered hornfelses (localities 6–11) are mostly found in the southern part of the gabbro, not far from the contact with Jurassic sediments, while the unlayered inclusions are most abundant towards the west. Only the larger clusters and individual xenoliths are indicated on the map.

The chief characteristics of the two types of inclusion may be summarized as follows:

1. *Granular pyroxene-hornfelses.*—These occur as homogenous masses having a fine, equigranular texture for all components. The only exceptions to this even granularity are provided by relict plagioclase phenocrysts and recrystallized amygdaloidal aggregates, both of which indicate derivation from primary igneous rocks. The granular pyroxene-hornfelses are generally dark rocks containing clinopyroxene in excess of other coloured silicates. There is never more than a feeble segregation of the various components into distinct layers. The surrounding gabbro maintains its normal character right up to the contacts with the hornfels masses, indicating that the incorporation of the latter did little to upset

the balance of phases crystallizing from the magma, and that metasomatism was probably negligible.

2. *Banded granular hornfelses.*—In these rocks both megascopic and microscopic layering is prominent. The layers may be several inches thick, and in that case they can be traced without discordance to the limits of available exposures which in some places amount to about

FIG. 9. Typical banded granular hornfels showing segregation of coloured minerals (mainly olivine) into clots. Part of a long narrow strip of hornfels from locality 7, Stacan Dubha.

20 feet. They are frequently buckled and tend to thicken towards the crests of the miniature folds (fig. 9). Texturally each layer may be distinct, and each component may have its own mode of development: thus olivine and hypersthene frequently form sieve-textured porphyroblasts; magnetite occurs as octahedra embedded in plagioclase, or occasionally as irregular grains with narrow coronas of pyroxene, amphibole, or mica; and the ubiquitous plagioclase is often fluxioned. The 'gabbro' surrounding these inclusions is generally very variable in composition and there may be narrow transition zones of anorthosite, troctolite, leuconorite, &c., between the normal gabbro and the xenolith. The chief mineralogical feature to note is the subordinate role often played by clinopyroxene in these layered hornfelses.

One of the most interesting of the banded granular hornfelses is a horizontal slab-like mass exposed on a vertical rock face by a fault-gully (loc. 9), a yard or so north of the point where the main footpath south of Beinn na Seilg descends into the gully. It is a dark ferruginous mass about 20 feet long and 3 feet deep, with prominent magnetite layers forming the uppermost 6–9 inches, and with a more homogenous granulite layer below, about 18 inches thick, composed chiefly of plagioclase and magnetite. A photograph of this inclusion is given in A. G. MacGregor's paper[1] (6), showing drag-folding of the upper surface of the inclusion and also variation in the composition of the gabbro adjacent to the inclusion. The normal gabbro consists of labradorite (60 %), augite (20 %), olivine (5 %), hypersthene (4 %), and magnetite (1 %), and towards the inclusion this passes into a zone of augite-troctolite about 6 inches thick, with 17 % of olivine and only 8·5 % of augite. Immediately adjacent to the inclusion proper there is a narrow zone of anorthosite. The following sequence of layers from the top of the inclusion downwards illustrates a very small part of the type of variation that may be seen in many of these rocks (fig. 10):

1. 4 mm. layer of fluxioned plagioclase.
2. 3 mm. layer of similar felspar with tenuous ophitic olivine grains.
3. 1·5 mm. layer of plagioclase with trains of euhedral magnetite grains.
4. 4 mm. layer with large sieve-textured olivine crystals and plagioclase.
5. A layer rich in magnetite rimmed by coronas of hypersthene in some cases and colourless amphibole in others.

No two of these banded rocks are alike. Associated with the hercynite-bearing hornfelses already described (p. 725) there are olivine-plagioclase-hornfelses, with a development of poikiloblastic crystals rivalling those shown in fig. 10. On Stacan Dubha (loc. 7) a slender belt of banded hornfels can be traced intermittently for over a hundred yards, with a characteristic development of the coloured minerals in clots, as shown in fig. 9. West of Beinn na Seilg (loc. 9) there is another occurrence of banded olivine-plagioclase-hornfels with the olivine this time in the form of small, somewhat rounded grains, and augite as occasional poikiloblastic crystals enclosing minute granules of plagioclase and olivine.

Another striking example of banded hornfels is provided by a strip

[1] The choice of this particular photograph to illustrate a paper devoted to pyroxene-granulite-hornfels was perhaps not a happy one, for pyroxene is a very minor constituent of this inclusion.

which is less than a foot in width, exposed for several yards on the shore north of Sanna (loc. 11). This has a steep dip, and lies parallel to the neighbouring contact of the great eucrite. The layers are regular and conformable, though slightly puckered in places. They are of two orders

FIG. 10

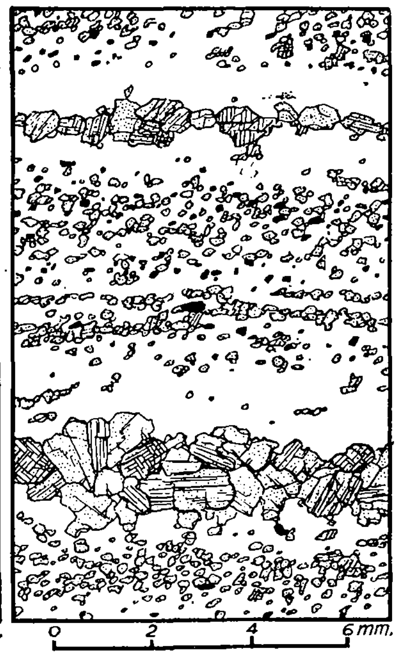

FIG. 11

FIG. 10. Banded granular olivine-hornfels, locality 8, south-west of Beinn na Seilg. The large sieve-textured patch of olivine is formed of one crystal. The plagioclase crystal boundaries have been omitted for the sake of clarity. They are slightly fluxioned parallel to the banding, and their size can be judged from the ophitic intergrowths with olivine shown near the top of the diagram.

FIG. 11. Banded diopside-bytownite-hornfels, locality 11, north of Sanna. The outlines of the plagioclase crystals have been omitted. They have an average diameter of about 0·5 mm.

of magnitude; the finer laminae are no more than a millimetre thick, while the stouter layers are spaced at intervals of about a centimetre, this spacing being so regular in some cases that it gives a strong suggestion of a rhythm. The proof that this rock is of sedimentary origin lies in its composition, for it is, in effect, a calc-silicate hornfels, with alternations of basic plagioclase (the most calcic to be found in any of the inclusions, with a composition of about An_{83}) and diopsidic augite. The latter is pale green and non-pleochroic, and its refractive indices (between about 1·68 and 1·70) and 2V (45° ± 2°) indicate a composition approximating to $En_{55}Fs_{10}Wo_{35}$. Small and irregular patches of epidote occur in association with the pyroxene, and also along shear-planes. Euhedral crystals of magnetite are fairly evenly scattered throughout the plagioclase-rich layers. The contrast between adjacent layers has been accentuated by diffusion of Fe and Mg to reinforce the pyroxene concentrations, resulting in the removal of all trace of coloured minerals on either side of each prominent dark band through a thickness of about a millimeter. Thus each pyroxene layer is flanked on both sides by narrow bands of pure anorthosite (fig. 11).

The special significance of this particular xenolith is that it displays the same granoblastic texture, the same degree of crystallinity, and the same style of banding as many of the other hornfelses described; but it also has — what the others lack — a composition that is closer, perhaps, to that of certain sedimentary rocks than to any normal igneous ones. Some marls and calcareous mudstones, for instance, have a high lime and alumina, and low silica content comparable with that of the hornfels, whose analysis is recorded in table III.

TABLE III. Analysis of banded calc-silicate hornfels, Sanna Point (loc. 11), Ardnamurchan. Analyst, W. H. Herdsman.

SiO_2	46·26	H_2O+	0·73
Al_2O_3	24·18	H_2O-	0·19
Fe_2O_3	1·38	CO_2	nil
FeO	3·96	TiO_2	0·16
MgO	3·58	P_2O_5	nil
CaO	17·67	MnO	trace
Na_2O	1·54		
K_2O	0·09		99·74

Origin of layered granular hornfelses.

Four possibilities may be considered concerning the origin of these layered hornfelses.

(*a*) Shearing of the gabbro accompanied by complete recrystallization, giving a kind of 'tectonic unmixing' of the various components, such as one may find between the micaceous and the quartz-felspar components in some schists. This mechanism is unlikely to be effective with the gabbroic mineral suite, and even if it were capable of producing a kind of layering, it would not be expected to produce the textural variation shown by adjacent bands in these hornfelses (cf. figs. 5, 9, 10, and 11).

In addition, many of the banded rocks show none of the mineral grain orientation that one would expect to find if the banding were of mechanical origin.

(*b*) Thermal metamorphism of banded gabbro. The hypersthene-gabbro is prominently banded in places, especially near its inner contact with later 'Centre 2' intrusions. Since some of the granular pyroxene-hornfelses may be derived from gabbro (see p. 728), it is natural to consider a possible connexion between banded-hornfels and banded-gabbro. In actual fact, however, the scale of layering in the two rock types is not comparable: in the gabbros the order of thickness is from a few centimetres to about a metre, while in the hornfelses the laminae may be from a millimetre to a few centimetres thick.

(*c*) Thermal metamorphism of bedded rocks (sediments or tuffs) of appropriate initial composition. There appear to be no sedimentary rocks which compare closely with these basic hornfelses in composition. A correlation might perhaps be made between the compositions of the hercynite-corundum-hornfelses and those of residual deposits rich in aluminium and iron; and between the diopside-anorthite-rock and a calcareous sediment such as a calcareous mudstone or even a greywacke. Even in these two most favourable cases there are difficulties. In the first instance one has to take into account the calcium and sodium of the felspar, and magnesium of the spinellid, none of which could be expected in any quantity in a residual deposit. In the second case the original sediment would need to be abnormally rich in sodium and almost completely deficient in potassium, which would be the reverse of the normal position with rocks containing a pelitic component. The hypersthene- and olivine-hornfelses are even more difficult to explain by non-additive metamorphism.

(*d*) Metamorphism and metasomatism of sediments. This is the preferred hypothesis: it is the only one that can account for the structure of the layering, for the mineral composition within the layers, and for the details of crystal habit such as the development of sieve-textured porphyroblasts. The latter provide evidence that diffusion processes have been in active operation.

Conclusions.

It was stated on p. 717 that the country-rock into which the gabbro magma was intruded is mainly sedimentary, yet the majority of the xenoliths appear, at least at first sight, to be of igneous origin. The recognition of the true nature of the banded granular hornfelses reduces the extent of this anomaly, although it does not remove it altogether. The paucity of stoped sedimentary country-rock fragments could conceivably be accounted for in part by the difference in specific gravity that exists between fragments of sediment and those of lava, the former perhaps floating and the latter sinking or remaining suspended in the magma at the present level of erosion. Such a sorting action depends upon the buoyancy of rock fragments in a 'magma' of unknown viscosity and an unknown state of crystallization at any stage in its history, and it is doubtful if xenoliths could move very far from their place of origin except with a magma surge, when they would all travel together, irrespective of density differences.

It is far more likely that their initial composition has determined the chances of survival of the different types of country-rock. Basaltic fragments no doubt survived recrystallization with little change in composition; but the chemically contrasted sediments probably suffered reaction, leading either to complete assimilation or at least to marked change in their composition. This possibility has hitherto not been considered in relation to the British Tertiary gabbros. For the early history relating to the development of such a concept, one has to examine various works on the inclusions in the Frankenstein gabbro of the Odenwald. Here, dike-like masses of pyroxene-hornfels occur which were thought by C. Chelius (1, p. 4) to cut the gabbro, and he described them as gabbro-aplites or beerbachites. E. Kalkowsky was the first to recognize them as inclusions of material older than the gabbro, and later G. Klemm suggested their derivation from various mixed sediments and tuffs (5). These conclusions were questioned by A. G. MacGregor (6), partly because some of Klemm's 'sedimentary' xenoliths had the textural characteristics found in baked lavas of the British Tertiary province: and partly on account of the difficulties of equating the composition of these basic hornfelses with those of known sediments. This conflict of views may be reconciled, (i) if a broad twofold division is recognized in the rocks concerned, as outlined on p. 728; and (ii) if the full impact of metasomatism is realized.

F. F. Grout (2) appears to be the first geologist to have recognized, or rather to have assumed, the large scale operation of metasomatism in converting Virginia slates around the Duluth gabbro into 'pyroxene-granulite' xenoliths. Although he quotes a number of analyses, there is too great a gap between those of the contact-altered slates, and of the supposedly further altered granulites, to give a convincing picture of the chemical aspects of basification. Unfortunately, the present account does nothing to close that gap; but it does present critical evidence to show that such basification of various types of sediment is indeed a reality.

This conclusion, which is based largely upon details of structure and composition of isolated xenoliths, is greatly strengthened by the recent discovery made by M. S. Sadashivaiah (12) of layered basic hornfelses in their proper field setting, interbedded with cordierite-hornfelses, &c., of the Macduff slate group in contact with the Insch gabbro, Aberdeenshire. These basic hornfelses duplicate many of the features of the xenoliths in the Ardnamurchan hypersthene-gabbro, including the development of sieve-textured olivine porphyroblasts.

In the present state of knowledge the writer is not prepared to extend the hypothesis of basification of sediments to include any basic hornfelses other than those which carry an imprint of their past history in their own structure. Future work will probably show that such an extension is necessary, to cover many of the less spectacular 'pyroxene-granulites' which have no conspicuous structures, and which at present are classed as *incertae sedis*, or are assumed to be of igneous origin.

The writer wishes to acknowledge the kind help he has received, in the field from Dr. J. E. Richey, and from discussion with Professor H. H. Read, Dr. A. K. Wells, and Dr. S. R. Nockolds. The cost of the analyses was covered by a grant from the Central Research Fund of the University of London.

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