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Some relationships resulting from the intimate association of acid and basic magmas

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SUMMARY

Evidence is presented from Guernsey, Iceland, Ireland, and Scotland that basic and acid magmas have commonly come together. Examples of this are found in surface extrusions and tuffs and in intrusions of various sizes formed at different depths. The basic magma has commonly been chilled against the acid, and the relationships indicate that the acid component was highly mobile; these two facts are thought to be intimately related, in that the mobility of the acid magma is due to the transfer of heat from the basic magma.

Consequences discussed include the question of the relative age of contiguous intrusions where basic rock is veined by acid: the age-sequence may be the reverse of that normally postulated. The possibility is also considered that basic magma may occasionally be necessary for the uprise of acid magma to high crustal levels.

1. Introduction

WE ARE impressed by the widespread evidence for the co-existence, side by side, of acid and basic magma.[1] The examples described in this paper range in environ-

[1] In this paper the terms *acid* and *basic* are used in an extended sense to include near-acid and near-basic types.

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ment from surface extrusions through minor intrusions to relatively deep-seated masses. They come from different geological periods and are geographically distributed from Iceland to Scotland, Ireland, and the Channel Islands. The relationships described may be much more widespread and significant than is at present realized. In our opinion they are often misinterpreted.

2. Composite lava-flows

In the Tertiary volcanic region of eastern Iceland five examples of composite lava-flows have been found; each is made of two components, one acid, the other basic (Gibson & Walker 1964). Four of these are visibly joined to their dyke-feeder, which is also composite. The proportion of rhyolite varies from 10 to 90 per cent in different composite lavas. There is unequivocal evidence that these composite bodies are surface extrusions; each flow rests on, and in turn is overlain by, bedded acid tuffs which later basaltic lavas overlap.

The strongest evidence for the simultaneous eruption of two magmas is the geometrical arrangement of the two components. The rhyolite everywhere overlies the basalt: in one example there is a layer of uniform thickness of basalt underlying the rhyolite; in others, when one of the components thickens, the other thins antipathetically. The contact between the two components is everywhere sharp; in places the basalt is chilled against the rhyolite. Where (rarely) rhyolite veins the basalt, the basalt is not chilled against the acid veins. A flow-structure parallel to the mutual contact is in places developed in the acid and basic components.

The rhyolite component is characterized by the presence of basalt xenoliths, which may represent 10 to 20 per cent of the total mass. These are similar in composition to the basic component, but are appreciably finer in grain; we interpret this as due to the chilling of the basic magma. These xenoliths commonly have crenulate[1] margins and are therefore unlikely to be fragments of pre-existing solid basalt. We conclude that the basic material was liquid when it was incorporated into the acid magma as xenoliths.

We are convinced that the two contrasted magmas were erupted at the same time in these composite lavas; we consider it likely that basalt began to appear on the surface before rhyolite, and that rhyolite continued to be extruded after emission of basalt had ceased.

3. Acid–basic mix-lavas and mix-intrusions

There are several occurrences in eastern Iceland of acid lavas that contain basic inclusions. The amount of basic material varies from less than 10 per cent to as much as 50 per cent. The basic rock is invariably fine-grained and is commonly glassy. Some of the inclusions are equant in form, with crenulate margins; some

[1] *Scalloped* ('having an edge cut into a series of segments of circles like a scallop-shell') might be a more appropriate word for some examples. The circles are always convex towards the acid rock.

form wisp-like bodies; others are vesicular and contain acid rock in the vesicles. We consider that the basalt was liquid when it was incorporated as inclusions in the acid magma.

One of the best examples occurs on the south slope of Helgustadafjall, Reydarfjördur in eastern Iceland (I.L.G.). This rhyolite lava, 100ft thick, contains 5 per cent of basic inclusions. These inclusions have the same general characters as the inclusions in the acid components of the composite lavas described above (Pl. 9a).

An intrusive equivalent of a mix-lava is perhaps afforded by the famous Loch Bá felsite ring-dyke of Mull. In the vicinity of Loch Bá itself the felsite (72·66 per cent SiO_2) contains a fair abundance of inclusions (Pl. 9c), many of them wisp-like, of an extremely dark fine-grained basic rock (56·91 per cent SiO_2). These inclusions are of chilled basic material. Their shape and grain-size make it extremely unlikely that they can be fragments of a pre-existing solid basaltic rock. Further studies on this and other acid intrusions in Mull that contain similar basic inclusions are in progress (Miss D. E. Burton, personal communication).

4. Tuffo-lavas

The term *tuffo-lava* was used by Abich in 1899 (quoted by Shirinian 1963) to denote extrusive rocks intermediate in character between tuffs and lavas. This category probably includes several Icelandic examples that show evidence of having passed through a fragmental stage but also have many of the characters of lavas.

A group of tuffo-lavas occurs on the hill Maelifell, 3 miles north of the Austurhorn intrusion in south-east Iceland (D. H. B.). This hill is made up predominantly of agglomerates and tuffs, intimately related in origin to a major Tertiary central volcano: the Álftafjördur volcano. Intercalated in the pyroclastic pile are several pitchstone sheets averaging 6ft thick, the individual sheets varying little in thickness within the confines of the visible exposures. The sheets contain many small inclusions of rhyolite and basalt, seldom more than 1in across, set in a pitchstone matrix that has a streaky flow-like structure parallel to the base of the sheets.

In thin section the matrix is mainly a near-colourless porphyritic acid glass (n 1·503–1·507) with a vaguely defined eutaxitic texture. Wisp-like basaltic fragments (Pl. 9b) make up about 10 per cent of the rock total; they vary from a clear brown glass (n 1·602 average) through near-opaque glass to fine-grained basalt.

The glassy nature of many of the basalt fragments and their wisp-like form indicate that the basalt was still liquid when it was incorporated into the acid magma.

The 'emulsion rock' from the Breiddalur volcano, also in eastern Iceland (Walker 1963, pp. 47, 62), differs in detail from the Maelifell sheets. The mass occurs as a tabular extrusion interbedded with agglomerates and also as an intrusion that was clearly the feeder. In thin section the rock consists of an intimate mixture (Pl. 10) of colourless acid glass and near-opaque basaltic glass in roughly equal proportions, both containing phenocrysts. This example represents a chilled mixture of acid and basic magmas.

5. Tuffs

Many acid tuffs contain some basaltic fragments, and it is commonly thought that these represent fragments of pre-existing solid basalt. It is possible, however, that they were liquid at the time of eruption. This seems to apply to the Skessa welded tuff (Walker 1962), in which the basalt forms 'bubbles' of dark brown glass in the acid matrix. It seems to apply also to many other Icelandic tuffs that contain vesicular basic fragments in addition to the acid pumice; for instance, some of the thick tuffs in Upper Geithellnadalur, where many of the basic fragments are glassy or near-glassy.

6. Composite minor intrusions

Composite minor intrusions, predominantly sills and cone-sheets, though dykes are also known, are characteristic of the Tertiary volcanic area of western Scotland and north-eastern Ireland. They have long been the subject of debate by British geologists (Harker 1904; Bailey *et al.* 1924; Richey & Thomas 1930); the most recent account is that by Bailey & McCallien (1956). A typical composite intrusion consists of a central acid component flanked by basic margins of tholeiitic dolerite. The acid centres vary from 10 to 150ft in thickness, but the basic margins are remarkably constant, almost all of them being from 2 to 4ft thick even where there are local irregularities in the form of the intrusion. The junction between the two rock-types is generally sharp. In places the marginal part of the acid component has been basified, and the heterogeneous, patchy, or streaky nature of the rock suggests that it was formed by the mixing of two magmas at a deeper level. The basic margins contain xenocrysts of those minerals that occur as phenocrysts in the acid centres; we believe that this has resulted from the mixing of basaltic magma with porphyritic acid magma before intrusion.

In certain intrusions the basic margin is chilled against the acid centre, indicating that the acid magma was emplaced when the basic magma was only partially crystallized. A few acid veins cut the basic margins, and in this situation the basic rock is not chilled against these veins. This is explained by supposing that the acid component remained liquid longer than the basic. The central acid component contains xenoliths of material similar to that of the basic margins. Many of the xenoliths, however, are finer in grain-size than the basic margins, and xenoliths have been noted that are fine-grained marginally. The basic xenoliths typically have crenulate margins. This, together with the other facts, suggests that when incorporated into the acid magma the basic material was in a liquid or pasty condition.

Composite dykes are locally abundant in the Tertiary volcanic region of eastern Iceland; several scores of occurrences are now known. In most of their characters they resemble the British examples although they are more variable in thickness, ranging from less than a foot to around 100ft. As mentioned earlier, several of these have given rise to composite lava-flows.

In composite intrusions of the type described here, the materials that formed the

basic margins and the acid centre were emplaced practically at the same time, the basic perhaps slightly before the acid.

7. Intrusive granitic pipes

The occurrence of acid pipes in intrusive basic rocks, as in the Tertiary centre of Slieve Gullion (Elwell 1958) and in the Hercynian intrusive complex of Guernsey (Elwell *et al.* 1960), is difficult to explain except on the view that the acid and basic materials were both unsolidified at the time of formation of the pipes. At Slieve Gullion the pipes are regularly vertical, and in Guernsey (Pl. 8c) they are inclined at about 30° to the horizontal in a south-south-east direction, there being little variation in plunge. At both places the pipes are straight or nearly so, and show a limited variation in diameter, mainly between 1½in and 4in. The pipes are connected downwards with sheets of acid material within (Slieve Gullion) or beneath (Guernsey) the basic host-rock. Because of their regularity it was considered that the pipes were formed by the rise of magma from the acid sheets into the heavier basic magma, the circularity of cross-section being determined by surface-tension effects. The localization of pegmatite along the upper surface of each of the inclined Guernsey pipes provides further evidence of a magmatic origin.

8. Net-veined intrusive complexes

In many intrusions containing both basic and acid components the basic rock is locally veined by the acid, sometimes intimately. There is often good evidence that the two components were in the condition of magma at the same time. The relationships in these net-veined complexes vary from a situation in which the basic rock is veined by acid rock to one in which the acid rock is dominant and contains inclusions of the basic rock.

(A) GUERNSEY

Acid veining in the Hercynian sheeted diorite complex of north-eastern Guernsey, Channel Islands, was described by Elwell *et al.* (1962). The dominant veins (average thickness about 1 in) are in the main parallel to the sheeting in the diorite and were termed *sheet veins*. They are linked at intervals by cross-connecting veins. The contacts of the sheet veins are sometimes highly irregular, having upward or downward projections (Pl. 8b). There is evidence of flow in the acid material, marked by the preferred orientation of feldspar and hornblende. The evidence of flow indicates that the veins did not form metasomatically, and the highly irregular contacts are not such as would be expected if the host-rock had been solid when the vein material was intruded. The diorite becomes progressively finer in grain over the last ½in towards the sheet veins, and within this more fine-grained edge feldspar phenocrysts are smaller and less numerous. We consider that the finer-grained edges of diorite against the acid veins are due to chilling and show that the diorite had not consolidated when the veins were formed.

We therefore think that in these veined diorites the acid veins formed before the host-rock was completely solid, and that they provide yet another example of relationships between acid and basic rocks that were developed when both members were unconsolidated.

(B) AUSTURHORN

One of the larger Tertiary intrusions of south-eastern Iceland, that of the Austurhorn (being studied by D. H. B.), includes a net-veined complex covering an area of about 1·5 square miles. This net-veined complex is characterized by rounded, pillow-like masses of dolerite surrounded by granophyre (Fig. 1; Pls. 7 and 8a). The pillows, in shape reminiscent of basaltic pillows in a pillow-lava erupted into water, vary from under 1 ft to over 30 ft across. Most of the pillows occur in

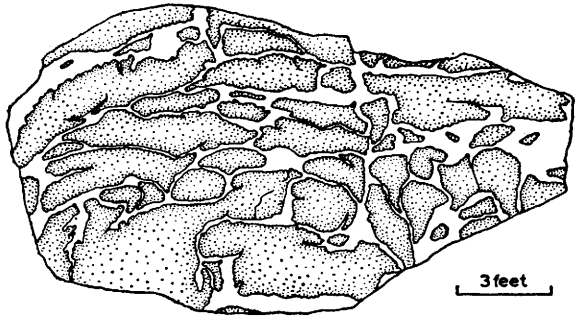

FIG. 1. Field sketch of an exposure in the Austurhorn net-veined complex showing closely spaced basic pillows separated by granophyre. The pillows have fine-grained margins: the grain-size is indicated by the closeness of the stippling on the sketch.

aggregates, individual pillows being separated from each other by thin layers of granophyre. The pillows generally have sharp contacts with the acid rock, although in places one rock grades into the other. Those with sharp contacts have dense, fine-grained, and crenulate margins that are in places cut by thin acid veins given off from the granophyre. The rock grades from a fine-grained basalt at the margin of a pillow to a much coarser rock, often doleritic, at the centre. The grain-size increases towards the centre of a pillow; this increase is most marked in those pillows that have a dense basaltic margin and sharp external contacts. The granophyre does not become finer grained towards the basic pillows.

In thin section the rock in the centre of the larger pillows is seen to be an ophitic dolerite composed of plagioclase, augite, and iron ore. Towards the margins of a pillow the grain-size gradually decreases and augite begins to give way to hornblende. At the margin itself the rock is usually a holocrystalline sub-variolitic basalt, with plagioclase as skeletal crystals and in sheaf-like aggregates; also present are skeletal opaque ore, hornblende (the main ferromagnesian mineral), and commonly biotite. Feldspar phenocrysts are common in the pillows, and they generally increase in number, but not in size, towards the centre of the pillow.

From their shape and their crenulate margins it is believed that these basic pillows were formed when basic magma was injected into acid magma. The fine-grained margins to the pillows are regarded as due to chilling of the basic magma against the cooler acid. As well as being chilled the basic material in some of the smaller pillows has also been metamorphosed by the granophyre with the production of hornblende and biotite.

(c) OTHER EXAMPLES

Relationships almost identical with those described above in the Austurhorn intrusion are encountered elsewhere: the Vesturhorn intrusion in south-eastern Iceland; the net-veined intrusion of centre II, Ardnamurchan; the Carlingford and Slieve Gullion complexes in Ireland (Bailey 1959; Bailey & McCallien 1956); and, to judge from the published description, St Kilda (Wager & Bailey 1953).

9. Survey of the literature

The examples quoted below show how widespread and significant may be the close association of acid and basic magma, which can, we think, account for many features previously explained in other ways.

The Gardiner River complex consists of intermingled basic and acid rocks and was interpreted by Fenner (1938, 1944) as due to the melting of a solidified basalt lava by a rhyolite flow. Wilcox (1944) rejected this view and regarded the complex as produced by the mixing of synchronous but originally separate flows of basalt and rhyolite. We follow Hawkes (1945) in believing that the mixing of acid and basic magmas probably preceded the extrusion of the lava. Also, it should be noted that Boyd (1961, p. 403), who records three additional 'mix-lavas' from Yellowstone Park, writes of one of them that it 'shows conclusive evidence of the simultaneous fluidity and mingling of rhyolite and basalt'.

A further example is provided by two pyroclastic deposits associated with the Katmai eruption of 1912. Fenner (1920, p. 583, and fig. 11) described how some of the pumice shows a banded or variegated structure with two components of contrasting composition: one containing 60·4 per cent SiO_2 and the other 74·7 per cent SiO_2. He explained this feature as due to fusion and incorporation of pre-existing andesite by the acid magma, but Williams (1954, p. 326) after revisiting Katmai, came to the conclusion that 'the hybrid character of the avalanche deposits was not caused by near-surface assimilation of old rocks by rhyolitic magma, but by simultaneous discharge of fresh rhyolitic and fresh andesitic magma from the same or closely adjacent vents'.

Wager & Bailey (1953) were the first to suggest that certain basic pillow-like masses in granophyre at St Kilda and Slieve Gullion could have been formed by the injection of basic magma into acid magma, in a manner analogous to the formation of pillow-lava in water. Wager & Bailey considered the basic pillows to have been chilled against the acid magma. They also pointed out (p. 68) that: 'Where, however, the basic magma had solidified and then been fractured and penetrated by the still liquid acid magma, it does not show a fine-grained selvedge'.

The reader is referred to the papers by Bailey (1959) and Bailey & McCallien (1956) for the subsequent development of these ideas.

Chapman (1962) gives a comprehensive account of some intrusive dykes in Maine that are composed of pillow-like bodies of diabase enclosed in a granitic or granophyric matrix. After considering many possibilities, and rejecting the idea that two magmas existed together in these dykes, Chapman concluded that the diabase was intruded as dykes into pre-existing gabbro and was later partially granitized: the diabase was locally replaced by acid rock. We consider that the observations recorded by Chapman are much more compatible with an origin by 'commingling' (Chapman 1962, p. 556) of two separate magmas than by granitization. Our reasons are as follows:

(*a*) It seems inconceivable that the physical differences between the diabase and gabbro are sufficient to result in the former being granitized and developing a 'pseudochill' zone against the granite whilst the latter shows neither granitization nor 'pseudochilling'. In the extreme case, Chapman believes that the diabase dyke has been almost wholly replaced by acid rock apart from a few scattered xenoliths, despite the fact that the gabbro wall-rock is totally unaltered. This we find particularly difficult to accept.

(*b*) We regard the 'pseudochill' zone developed about each diabase pillow as being a true chilled margin. We have examined undoubted chilled margins of many basic minor intrusions and commonly find swallow-tailed, H-shaped plagioclase in them: such plagioclase is diagnostic of a chilled margin. Chapman records the occurrence of similar plagioclase in his 'pseudochill' zone but rejects an origin by chilling, instead claiming (p. 554) that: 'Through recrystallization in the pseudochilled zones they have come to resemble the skeletal crystals of genuine chilled zones.' We cannot accept such a conclusion. Chapman produces as further evidence against chilling that glass is absent from the pseudochill zone. This we regard as purely negative evidence, for glass is absent from the majority of basic chilled edges, except where there has been drastic chilling, as in a pillow-lava.

(*c*) The sharp sutured contacts between the acid and basic rock, which in Chapman's opinion (p. 558) 'are not to be expected when basic melt chills against acid melt', are in fact common in composite lavas and minor intrusions, such as those described above, where granitization cannot seriously be entertained as a working hypothesis.

From the evidence presented we think that in the Maine dykes the two magmas, one basic and the other acid, were injected essentially simultaneously. Other features of Chapman's dykes, for example the skialiths, can be easily explained by such an origin.

Among other examples of the association of basic and acid rocks in conditions that suggest simultaneous liquidity are the so-called 'relict dykes' in many granite masses, such as those in British Columbia (Roddick & Armstrong 1959), the Ballachulish granite in Scotland, and the Slaufrudal stock in Iceland (A. E. Beswick, personal communication). These dykes apparently cut the granite, but are themselves veined by it. We think that in some instances dykes are intruded into partially fluid granite magma and that the granite magma subsequently veins the dykes.

There is the further possibility that many of the mafic xenoliths so common in granites and granophyres may have been in the condition of liquid basalt when they became xenoliths; the tacit assumption that such xenoliths are always fragments of a pre-existing rock should be reconsidered.

10. Summary and conclusions

We are convinced that basic magma can be, and commonly is, chilled against acid magma; that the fine-grained margin of basic rock adjacent to acid rock we have described in the examples above is, in fact, a chilled margin. Some metamorphic effect, for example the development of hornblende and biotite, may also be present but it is quite distinct from the chilling. The chilled margins vary in thickness from less than an inch to perhaps more than 10ft, and there is a progressive increase in grain-size from the contact. The acid rock is never itself chilled against the basic rock.

The geometry of the acid and basic components in some of the occurrences described above can be explained only by postulating simultaneous liquidity of the two magmas. Such occurrences include the arrangement of basalt and rhyolite in a composite lava-flow and its feeder; the cylindrical shape and straightness of granophyric and granitic pipes, as at Slieve Gullion and in Guernsey; and the pillow-like form of many of the basic masses in net-veined complexes. Various other features are consistent with simultaneous liquidity: the crenulate margins of basic masses; the wisp-like form of basic inclusions in some other examples; and the occurrence on occasion of acid veins cutting basic material that is chilled against the acid veins.

Although it is generally accepted that basic magma is normally less viscous than acid magma the relationships in the net-veined complexes seem to suggest that the reverse was true under the conditions that obtained in these complexes. The acid rock forms an intricate network of veins, many of them extremely thin and extending for long distances. Additional evidence for fluidity is seen where the basic rock is markedly chilled against thin acid veins. There is often no correlation between the thickness of the vein and the thickness of the basic chilled margin adjacent to it; it is likely that either there has been a continuous flow of cooler acid magma through the vein, or that there was originally much more acid magma, which has subsequently been squeezed out by the settling of basic masses.

There is thus evidence that the acid magma was very fluid. It is possible that this was due to its being highly charged with gas. The granophyre is commonly drusy and the druses contain hydrous minerals. In some examples the granophyre that veins the basic rock is notably richer in drusy cavities than is normal. Another, more likely, explanation of the increased mobility of the acid magma is that it was heated by the basic magma. The existence of chilled margins indicates heat transfer at the contact with the acid magma. In certain veined pillows, and perhaps in pipes, it seems that the intruding acid magma became hotter the farther it penetrated the basic magma; the evidence is the disappearance of the basic

chilled margin as the intruding acid material is followed inwards and the merging of the acid and basic rocks in the centres of some pillows and in the upper parts of the Slieve Gullion pipes.

That the basic magma was relatively viscous is shown by the absence of basic veins cutting the acid rock; we know of no example of a net-veined complex in which the veins are of basic rock cutting acid. The shape and, often, the size of the basic pillows of a net-veined complex are remarkably similar to those of basalt pillows in a pillow-lava; since water is much more fluid than basic magma, by analogy it would seem that the acid magma in net-veined complexes must likewise be much more fluid than the basic magma.

The conclusions above were reached purely from a consideration of the field relationships of acid and basic rocks. There is some support from recently published experimental work (Shaw 1963; Friedman *et al.* 1963), which shows that an acid glass raised 100 deg C in the temperature range 700°C to 1000°C experiences approximately a tenfold decrease in viscosity. Suppose that the acid magma forming the veins in a net-veined complex had a viscosity of about 10^5 poises (a typical basalt lava has a viscosity of between 10^3 and 10^5 poises). Shaw's curves indicate that such a viscosity is attained by an acid magma at 1000°C containing 4 per cent by weight of dissolved water, or by one at 900°C containing 6 per cent dissolved water. Such high water contents do not appear unreasonable. Independent evidence from zeolite distribution data suggests that the Austurhorn net-veined complex was formed at a depth not exceeding 6000ft; at this depth the solubility of water in acid magma at 900°C is about 4 per cent (Goranson 1931, p. 494).

The discussion on net-veined complexes has an important bearing on the problem of determining the relative ages of contiguous acid and basic intrusions. The fact that a basic intrusion is locally cut by veins issuing from an acid intrusion does not necessarily mean that the emplacement of the basic mass as a whole pre-dated that of the acid mass. In net-veined complexes such as that of the Austurhorn the basic pillows may result from basic magma coming into acid magma, and to this extent the basic component may be later than the acid. The fact that the basic rock is itself cut by acid veins is due to the basic magma having solidified first. Some net-veined complexes may have resulted from the mobilization of a pre-existing acid rock by a basic intrusion; the mobilized acid material would then have back-veined the basic intrusion (Hughes 1960, p. 114; Wadsworth 1961, p. 57).

Fig. 2 is an attempt to show diagrammatically a possible situation in which a net-veined intrusion, a composite dyke, and a composite lava could originate and how they may be related to one another structurally. In Fig. 2a a basic dyke is shown transecting a body of acid magma (or potential acid magma). The dyke is able to do this if the acid material is so viscous that it fractures (as does pitch) under the action of rapidly applied stress. In Fig. 2b the acid magma adjacent to the dyke has been heated up by the basic magma and its viscosity reduced to the extent that the basic magma can no longer pass through it in the form of a dyke but instead forms pillows. Further, the mobilized acid material now starts to rise along the hot and perhaps still-liquid centre of the basic dyke. The continued uprise of basic magma (Fig. 2c) into the acid magma results in the mobilization of

much acid material; thus we account for the fact that the thickness of the acid component of composite intrusions bears no relationship to the width of the basic margins. In the situation illustrated a composite lava is shown to result when the composite dyke attains the surface.

Some would interpret the intimate association of basic and acid material in the varied environments discussed in this paper as evidence for liquid immiscibility. We do not take this view. Instead we believe that two magmas of contrasted com-

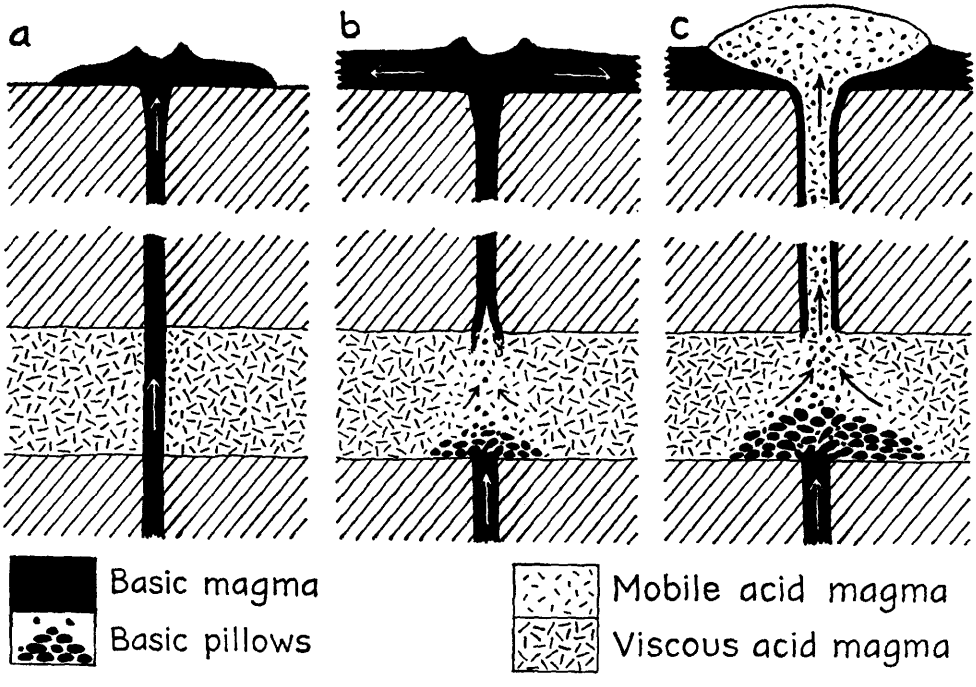

FIG. 2. Diagrammatic representation of the possible relationship between, and origin of, a net-veined complex of Austurhorn-type and a composite dyke feeding a composite lava-flow.

position have come together; in some instances the development of a chilled margin to the basic magma has effectively separated the two magmas and has inhibited mixing; in other instances the two have cooled too rapidly for mixing to occur.

Finally, we offer some general comments on the relationships between acid and basic magmas. There is evidence in net-veined complexes that the presence of basic magmas increases the mobility of the acid magma. Further, in the areas we have investigated, it would appear that acid magma has reached high crustal levels more frequently as a component of composite intrusions than as purely acid minor intrusions: composite dykes and sills are more common than acid dykes and sills. We suggest that acid magma normally experiences great difficulty in attaining high crustal levels but this difficulty is eased when it comes in contact with basic magma. The presence of basic magma may, indeed, be essential to the uprise (and

perhaps even the generation) of acid magma in geological environments of the type with which we are concerned.

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PLATES 7–10

PLATE 7

(*a*) Group of closely spaced basic pillows in the net-veined complex of the Austurhorn intrusion, south-eastern Iceland. Scale given by 9-in rule.

(*b*) Group of porphyritic basic pillows showing chilled and crenulate margins. Scale given by 9-in rule. Same locality as (*a*).

(*c*) Isolated basic pillow in granophyre. Same locality as (*a*).

PLATE 8

(*a*) Typical exposure of the net-veined complex of the Austurhorn intrusion, showing granophyre veins cutting basic rock. The basic rock shown is the upper part of a very large pillow, with grain-size decreasing upwards. Scale given by 9-in rule.

(*b*) Acid veins in diorite in the net-veined complex of Beaucette, north-eastern Guernsey. The veins show swellings, discontinuities, and projections. Scale given by matchbox.

(*c*) Inclined granitic pipes in metadiorite, Beaucette, north-eastern Guernsey. The pipes are inclined at 30° towards the reader.

PLATE 9

(*a*) Photomicrograph of rhyolite–basalt mix-lava, Helgustadafjall, eastern Iceland, showing a basic inclusion which contains a phenocryst of bytownite, in porphyritic rhyolite.

(*b*) Photomicrograph of tuffo-lava, Maelifell, south-eastern Iceland, showing a dark, wisp-like basic inclusion in acid glass, both being moulded around a rhyolite fragment. Another basic inclusion in the top left-hand corner shows flow-structure. A small piece of basaltic scoria is seen in the bottom left-hand corner, together with other rock fragments and phenocrysts of andesine. ×40.

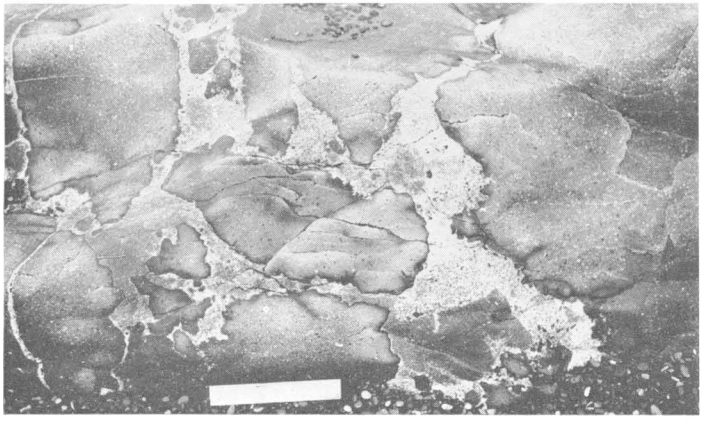
(*c*) Photomicrograph of a basic inclusion in felsite, one mile north-east of Loch Bá, Loch Bá ring-dyke, Mull, an example of a mix-intrusion. The basic rock shows flow-structure which conforms to that in the felsite. ×15.

PLATE 10

(*a*) Photomicrograph of 'emulsion rock' from Berufjardartindur, Breiddalur, eastern Iceland, showing a groundmass that is an intimate mixture of black basic glass and clear acid glass. Phenocrysts of bytownite are mantled by basic glass; those of sodic plagioclase are mantled by acid glass. ×30.

(*b*) A greatly enlarged photomicrograph of the groundmass of the 'emulsion rock' shown above. The basic glass is black, the acid clear. ×100.

a

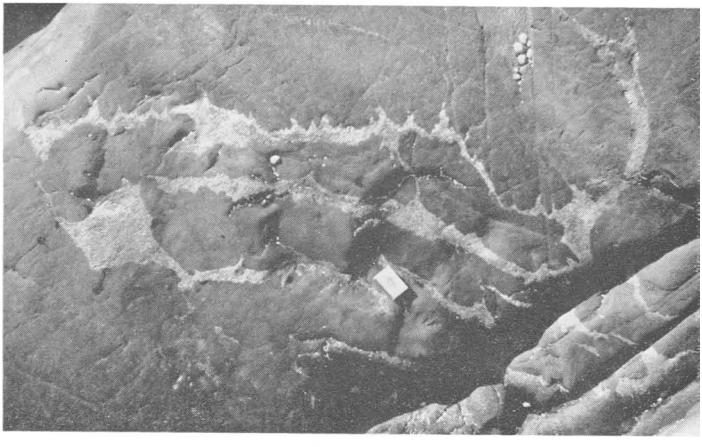


b

c

Basic pillows, Austurhorn intrusion, Iceland
(full explanation on p. 43)

a

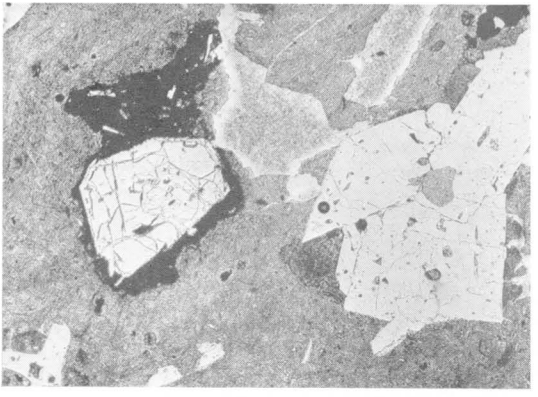


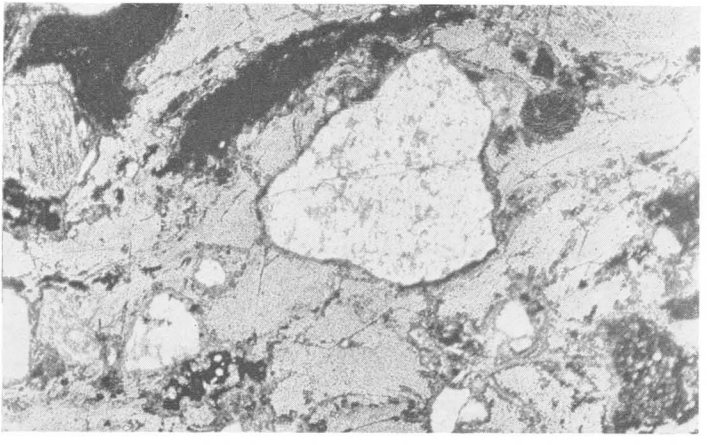
b

c

Details of net-veined intrusions, Austurhorn, Iceland, and Beaucette, Guernsey
(full explanation on p. 43)

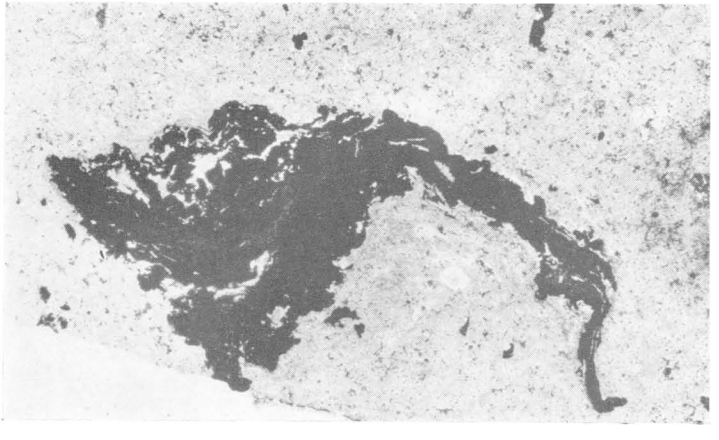
a





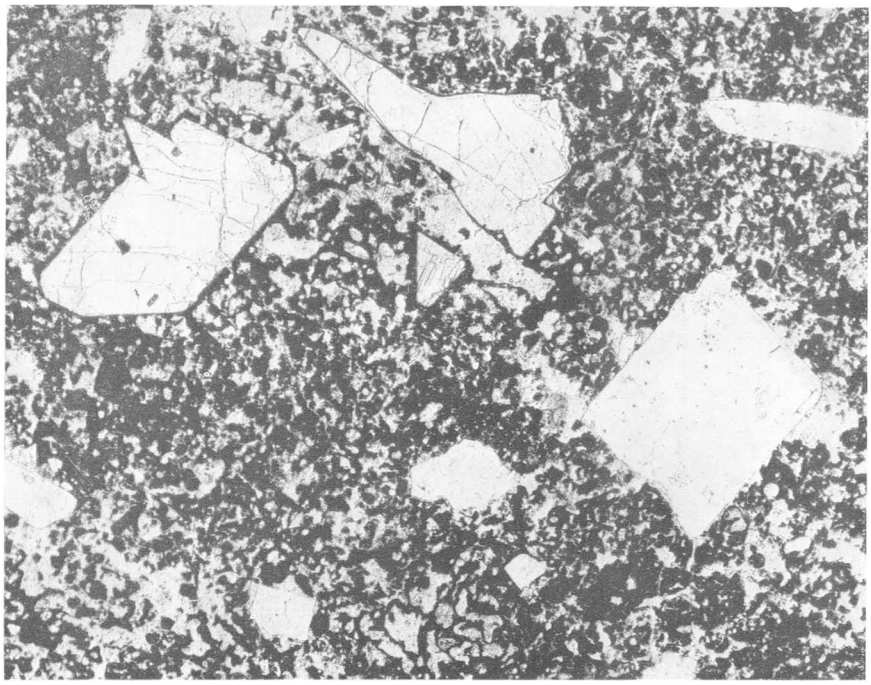
b

c

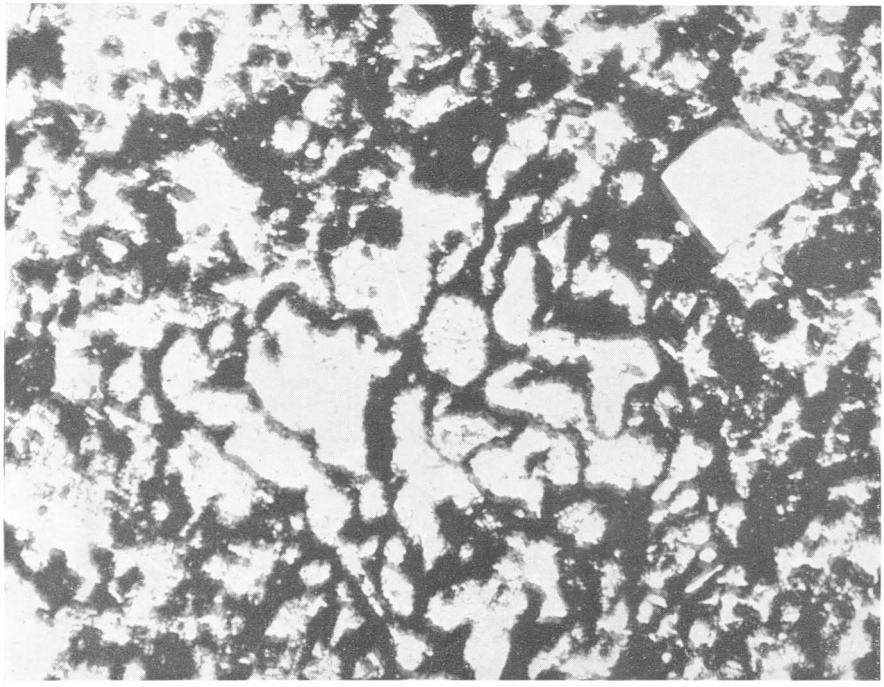


Photomicrographs of mixed extrusive rocks, showing basic inclusions
(full explanation on p. 43)

a



b



Photographs of 'emulsion-rock', Berufjardartindur, Iceland
(full explanation on p. 43)

DISCUSSION

Sir EDWARD BAILEY said that the paper concerned one of the most important subjects of present-day geological research. A reassessment was required wherever acid rock veined basic, etc. Discussion had been proceeding on these lines for a number of years. Analogies had been drawn between basic magma entering acid magma, and basic magma entering the sea. In some cases fuller analogy was afforded by the subglacial eruptions of Iceland, with their pillow-lavas, their melted ice, and their floods. Dr Doris Reynolds had drawn attention to this sort of thing in a paper on Slieve Gullion in 1937.

The AUTHORS agreed with Sir Edward Bailey that a reassessment was indeed required of the time-relations and genesis whenever acid and basic rocks were intimately associated. They would like to acknowledge the important contributions that Sir Edward had made on the subject of acid–basic relationships. The analogy with subglacial eruptions mentioned by Sir Edward was in fact very close; it was a few days after having studied the products of a subglacial eruption in south-east Iceland that two of the authors reinterpreted the Austurhorn net-veined complex, so impressed were they by the similarities between the basic pillows, whole and broken, in each.

Dr J. F. DEWEY said that the authors had presented excellent examples of contacts indicating the simultaneous intrusion and eruption of acid and basic magmas. The speaker had observed similar relationships in Lower Palaeozoic volcanic sequences in Ireland and North Wales. The Crogenen granophyre, south of the Mawddach estuary in Merionethshire, possessed, locally, a marginal selvedge of dolerite, and the dolerite–granophyre contact was complex with 'flames' of granophyre penetrating the dolerite. Dolerite 'load-casts' bulged into the granophyre and a few of them were completely detached. The dolerite was chilled against the granophyre and yet, in places, granophyre veins penetrated the dolerite. The evidence demanded the interpretation that the granophyre and dolerite were simultaneously intruded, developing complex, flowing, mutual relationships. Complex, 'flowed', dolerite–felsite contacts were also common in the Caradocian volcanic sequence in Co. Waterford. In the Lough Nafooey area (Co. Mayo), Arenig rhyolites carried 'balled-up' and 'pillowed' masses of spilites, again indicating coeval acid and basic magmas. Dr Rast and the speaker had discovered last year an interesting contact between dolerite and welded tuff near Tranmore in Co. Waterford, where the strong eutaxitic texture of the tuff, on approach to the contact, gradually became weaker until a devitrified acid glass was present at the contact. Load and flame structures dominated the contact, and clearly the dolerite magma, on intrusion, had melted the welded tuff. The speaker thought that, in spite of the obvious relationships just mentioned, it might sometimes be difficult to distinguish between the two situations: (*a*) where acid and basic magmas were intruded simultaneously; and (*b*) where basic magmas melted acid rocks; (*a*) and (*b*) would produce similar mobile contact relationships. Had the authors any criteria to offer by which one might distinguish between the two situations?

The AUTHORS replied that the phenomena described by Dr Dewey evidently developed under conditions similar to those that obtained for many of the structures they had described. They agreed with Dr Dewey that such structures indicated coeval acid and basic magmas. It might be impossible to decide, in an intimate association of acid and basic rocks, whether or not the acid component was produced by melting of pre-existing acid rock.

Dr A. C. BISHOP commented on the implications of the order of intrusion of acid and basic rocks at different tectonic levels. In the Tertiary volcanic province it had been established that acid and basic rocks were simultaneously fluid and that the basic magma often chilled against the acid one. The authors had drawn attention to Guernsey, but here the tectonic setting was different. The Channel Islands were part of an Armorican plutonic and orogenic region and care was therefore needed before concluding that intrusions in this setting could be interpreted in exactly the same way as those in non-orogenic areas. If the results of research on plutonic rocks in Jersey were compared with the authors' work on high-level Tertiary acid–basic relationships, then distinct differences as well as undoubted similarities became evident. First, the basic rocks were dominantly diorites and not gabbros, although the former were derived metasomatically from the latter. Secondly, in south-east Jersey there was the clearest field evidence that the diorite was emplaced before the granite and that the time-gap between the two was in one instance long enough for a suite of basic dykes to be intruded and to chill against the diorite. The solid diorite was remobilized by the granite and there were contact features that showed clearly that diorite and granite were simultaneously soft; but here the fluidity was acquired and not original.

It was evident therefore that in interpreting igneous contacts due regard needed to be given to the details of the mineralogy of the rocks involved, the depth of intrusion, and the tectonic setting. The granite controversy arose because just such factors were largely overlooked and its apparent resolution began when time and place were taken into consideration. The speaker suggested that, just as there were granites and granites, the intrusive phenomena between igneous rocks of contrasted composition might differ also with time and place.

In reply to Dr Bishop the AUTHORS said it was not their aim to consider the ultimate origin of the magmas concerned but rather to show that two contrasted magmas had often come together. They were interested to note that in Jersey the 'diorite and granite were simultaneously soft' and on this point there seemed to be no disagreement between Dr Bishop and the authors. However, the authors did not believe that the tectonic level was as important as Dr Bishop believed; in any event there was on Jersey a thick sequence of lavas that were associated with the plutonic complex, and this complex might therefore be a relatively high-level one and comparable to the Tertiary intrusions described in the paper.

Professor S. E. HOLLINGWORTH remarked that it was pertinent to recall that in 1937, in an excursion on Carrock Fell, Sir Edward Bailey had clarified the field-relations of the diabase. This appeared to have transgressive relations to the grano-

phyre, but against it the granophyre showed clear signs of local chilling. Sir Edward's interpretation in terms of remelting of the granophyre was one that had since become widely recognized.

Dr S. W. MOREL drew attention to recent work by Wilson, Bear, Gass, and others in Cyprus (*Mem. geol. Surv. Cyprus*, **1**, **2**, **3**, **4**, **7**). Mapping of well-exposed plutonic rocks some 6000ft in total thickness showed a layering in the Troodos plutonic series passing upwards from peridotite through harzburgite, wehrlite, pyroxenite, and gabbro into granophyre. It was clear from many occurrences that gabbroic and granophyric magma had coexisted in this layered complex. Examples of basaltic dykes intruded into granophyre and of gabbro and microdiorite intruded by granophyre were common. For the coexistence of both acid and basic magmas in one intrusion one had merely to postulate simultaneous tapping of magma from both layers; thus, place and time were the controlling factors.

The examples of mingling of magmas quoted by the authors presented no serious petrological problem. It was also possible for banded gneisses or granite to be melted by basaltic magma, and this in turn could also give rise to apparently coexisting acid and basic magmas. Too much attention was paid to small high-level occurrences that were inadequately exposed.

Professor B. C. KING said that the evidence for contemporaneity of basic and acid magma in the examples of volcanic associations was particularly impressive. That, however, presented for plutonic examples was much less convincing.

There was a risk of making generalizations that obscured real and significant variations in relationships. This was very true of composite sills, which were among the most striking examples of basic and acid associations. The observation of finer-grained margins to the basic against the acid members of composite sills was unusual; the absence of any internal chilled margin was characteristic.

The evidence of hybrid rocks in the sills, and particularly of the xenocrysts contained therein, pointed to mixing of two magmas, though not where the hybrids were seen. The typical arrangement of basic margins and an acid interior was, however, difficult to explain unless the basic magma was emplaced first and largely consolidated (cf. King, B. C. 1964. The nature of basic igneous rocks and their relations with associated acid rocks. Part IV. *Sci. Progr.* **52**).

The fact that the phenocrysts of the acid members of composite intrusions resembled those of independent acid sills and dykes did not suggest that the acid magma of composite intrusions was superheated. The presence of phenocrysts of quartz, orthoclase, and oligoclase pointed to temperatures of liquids corresponding to those of the cotectic phase boundary.

In reply to Professor King, the AUTHORS said they would refer to the examples of composite lava-flows that could be seen to connect with feeding composite dykes. There appeared to be conclusive evidence that the acid and basic components of these lavas flowed together, though the basic magma was extruded somewhat ahead. Similar conditions therefore obtained in the composite dyke-feeder; that is, the basic component could not have been more than partly consolidated when the acid magma came in.

Dr G. P. BLACK pointed out that there were often more than two hypotheses possible to account for the complex interrelationships found between acidic and basic rock masses in the Brito–Arctic province. For instance, the zone of 'intrusion-breccia' and net-veining found separating the granophyre of western Rhum from the basic and ultrabasic mass to the east had originally been interpreted by Harker as a straightforward case of acid magma invading and breaking up pre-existing rock. More recently its origin had been ascribed to later basic magma invading and melting pre-existing acid rock, the mobilized acidic material 'back-veining' the consolidated margin of the basic and ultrabasic mass. Detailed examination, however, favoured a third hypothesis. The zone truncated the structures of both its neighbours and contained as its predominant basic xenolith basalt and not gabbro, harrisite, or peridotite derived from its eastern wall. The zone was clearly an independent mass not genetically related to either of its nearest neighbours.

It was disappointing that the net-veined quartz-dolerites from Ardnamurchan were not included within the present paper, and the speaker looked forward to the forthcoming publication of an account of these rocks by two of the authors.

The AUTHORS replied that unfortunately they were unfamiliar with the Tertiary igneous rocks of Rhum. However, the third hypothesis, favoured by Dr Black, to account by the zone of 'intrusion breccia' and net-veining seemed very feasible and appeared to be similar to that proposed by the authors for the Loch Bá ring-dyke.

Subsequent written contribution from Mr D. BRIDGWATER, Mr P. DAWES, & Dr B. WINDLEY:

Most of the evidence presented by the authors for the coexistence of acid and basic magmas is taken from volcanic rocks, although by citing examples from Guernsey and by reinterpreting Chapman's observations from the Bays of Maine complex the authors imply that their conclusions may be applicable over a much wider range of geological environments.

Recent studies of acid–basic relationships formed under plutonic conditions in South Greenland have convinced us that features similar to those described by Chapman can be explained only by the interaction of two mobile rocks followed by replacement and recrystallization. Neither the authors' two-magma theory nor Chapman's replacement theory can alone explain all the features described. We suggest that the reason for this is that in plutonic environments the acid material remained active for a considerable period after the basic magma solidified and will therefore show dominantly replacive relationships against the basic rocks. Transitional types, such as those described from Guernsey, in which there is evidence for flow of the acid material and chilling of the basic material, may be expected but will be less common in truly plutonic rocks owing to the much slower rate of cooling in these conditions.

Relevant features from Greenland include:

(1) Noritic gabbro and diorite masses emplaced within late orogenic plutonic granites (Bridgwater 1963; see also Walton 1964, *Quart. J. geol. Soc. Lond.* **120**, 547). The relations between the basic and granitic rocks vary from chilling of basic material against acid to granite replacement of the basic rock. The two processes may sometimes be seen in the same hand-specimen. It is suggested that the basic rock was emplaced into a mobile granite which remained active after the basic rock solidified.

(2) Granite pipes with several features in common with those described by the authors but which were formed by replacement of the basic rock, possibly while the latter was still hot. The pipes can be seen to have been formed as the result of the rise of active fluids from horizontal pegmatites cutting the basic host. They show a change in petrography from bottom to top as follows: pegmatite,

coarse friable granite, medium-grained granite packed with potash feldspar megacrysts, granodiorite containing rounded feldspar megacrysts, diorite slightly enriched in potash feldspar, and diorite barely distinguishable from the host-rock.

(3) Dioritic dykes cutting the plutonic granites with margins showing flow-aligned crystals, original aphanitic texture, and thin apophyses. The dykes have been partly attacked by late activity in the granite with the growth of biotite and sphene at the expense of hornblende. In some instances local fine-grained margins appear to have acted as a protection against the effects of the granite. These dykes can be seen to have been emplaced into mobile granite and are not to be confused with relics of dolerites emplaced into cold rocks remobilized in a subsequent plutonic episode (see Watterson, in the press).

(4) Net-veined bodies. These rocks are generally similar to those from Guernsey and Ardnamurchan. The granitic component of the composite sheets has remained active after the solidification of the basic rocks, resulting in the formation of coarser-grained borders to the diorite pillows. These borders consist of recrystallized sphene and orthite aggregates, together with biotite formed at the expense of the original hornblende. Several of the diorite blocks are almost completely made over to granite and can be recognized only as slightly more basic pillows set in the granitic matrix (Windley, in the press). Other net-veined dykes cutting late plutonic granites contain basic blocks and pillows with original chilling against the granite veins. These chills have been partially recrystallized owing to the effect of the granitic net-veins, with the formation of biotite and chlorite from hornblende.

The recrystallization and replacement features described from Greenland are in agreement with the ideas put forward by Bishop (1963), who suggested that chilled margins are more common in volcanic environments and reaction-contacts more common in deep-seated environments. We therefore consider that the authors' ideas taken from volcanic rocks cannot be applied *in toto* to rocks formed under plutonic conditions where granite may be expected to have remained active long enough for replacement and recrystallization to take place. The authors' remarks on the need to reconsider the formation of basic schlieren can apply only to volcanic environments.

We also suggest that the term 'magma' in the sense of the complete rock-melts described by the authors from Iceland should be used with caution for acid rocks in plutonic environments. In these conditions mobility of the granitic component of composite bodies need not necessarily imply that there was a granite melt formed. Moreover, the distinction between assimilation and granitization becomes meaningless in plutonic environments. The nearest approach to a granite 'magma' in the sense used by the authors is seen in the net-veined bodies, where the granitic component shows a high degree of fluidity.

Although we agree with the authors that many of the features described by Chapman can best be explained by the interaction of two mobile rocks, this need not imply that recrystallization and replacement did not also have a role in the formation of net-veined bodies. In particular it seems likely that the 'pseudo-chills' described by Chapman could have been formed by recrystallization of an originally chilled contact.

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Windley, B. The composite net-veined diorite intrusives of the Julianehåb district, South Greenland. *Medd. Grønland* [in the press].

The Authors' reply:

It is interesting to hear of the occurrence of somewhat similar relationships, between acid and basic rocks, in what appears to be a more deep-seated environment.

Relationships resulting from the intimate association of acid and basic magmas

There seems to be a considerable measure of agreement between the authors of the contribution and ourselves. We concur in recognizing that certain phenomena have resulted from the intimate association of acid and basic magma and that basic magma has frequently chilled against acid magma. It seems to us reasonable to suppose that a chilled margin may subsequently become recrystallized, though it might be difficult to establish that this has in fact occurred.