MINERALOGICAL MAGAZINE, VOL. 45, 1982, PP. 201–9

Origin of some of the Rhum harrisite by segregation of intercumulus liquid

COLIN H. DONALDSON

Department of Geology, University of St. Andrews, St. Andrews, Fife KY16 9ST, Scotland

ABSTRACT. New field observations of certain harrisite occurrences are presented, including: interruption of layers; splitting of very thick layers into several smaller ones; existence of small isolated lenses and pods of harrisite and of upwardly extending tongues of harrisite; harrisite forming parts of the matrix of breccias; and isolated pods of harrisite along the western margin of the intrusion. These layers, lenses, tongues, and pods seem to have crystallized within the cumulus mush rather than at the mush–magma boundary. It is proposed that the rock in these instances represents segregated, intercumulus melt which 'ponded' beneath relatively impermeable layers in the cumulus mush. Several ways in which supercooling may have arisen to cause skeletal olivine growth are considered and previous estimates are thought to need reduction by 10–20 °C. It is suggested that segregation of upward-filtering melt in other layered intrusions might produce layers indistinguishable from 'uniform' cumulate.

AN uncommon but none the less intriguing type of igneous layering is that which Wager (1968) referred to as *crescumulate*, in which elongate, skeletal, or dendritic crystals are aligned at a high angle to the layering plane. Others have used the term *comb layering* for this type of layering (see review in Lofgren and Donaldson, 1975). To explain the origin of crescumulates, Wager and Brown (1968) adopted a petrogenetic scheme which Wadsworth (1961) had proposed for the crescumulates of the Rhum intrusion (so-called *harrisitic cumulates* or *harrisite*) in which cumulus olivine crystals lying on the top of the cumulus mush were bathed in supercooled melt convecting along the roof and sides of the chamber, and consequently grew rapidly upwards in elongate skeletal-dendritic fashion.

More recently, Chen and Turner (1980, pp. 2583–4) have described a 'double-diffusive convection' experiment in the H_2O-Na_2CO_3-K_2CO_3 system in which crystalline layers resembling the textures of crescumulates alternate with layers texturally similar to cumulates (see also Huppert and Turner, 1981, fig. 2). Irvine (1980, pp. 368–9) has suggested how crescumulate layers in the Muskox intrusion might form in the 'planar diffusive case' of a doubly diffusive convecting magma, and Rice (1981) has stated that the Rhum crescumulates represent the 'finger-diffusion case' of a crystallizing doubly diffusive convecting magma.

The present author has been re-examining the Rhum harrisite for some years and considers that the features of some 'layers' are at variance with the petrogenetic scheme which Wadsworth (1961) proposed. The purpose of this paper is to report these new observations, and to suggest that these harrisites crystallized *within* the consolidating pile of cumulus mush rather than at its upper surface. The conclusion highlights how the aspects of compaction and 'diagenesis' of igneous sediments have been neglected by petrologists in favour of the cumulus stage of crystallization.

Summary of Wadsworth's description and crescumulate hypothesis

Harrisite was named by Harker (1908) after rocks around Harris Bay (fig. 1). It is one of several types of rhythmic layering in the Rhum intrusion and is characterized by skeletal and dendritic olivines* which are absent from adjacent cumulate and which range from 1000 to 2000 mm in size. Individual layers have thicknesses of as little as 2 cm and as much as 12 m and are conformable with the cumulate layering (fig. 2*a–e*). Two harrisite layers are separated by one or more cumulate layers.

Wadsworth's observations of harrisite were made in the Western Layered Series where he distinguished several macro-units of cumulates, each of distinctive petrographic character (fig. 1). Harrisite occurs in only macro-units A, A/B, and B, though not uniformly; for example, layers of the rock type are more abundant at the bottom and top of the Ard Mheall Series than in the middle (Wadsworth, 1961). Harrisite layers have bulk

---

* Detailed descriptions of these crystals have been presented by Donaldson (1974 and 1976).

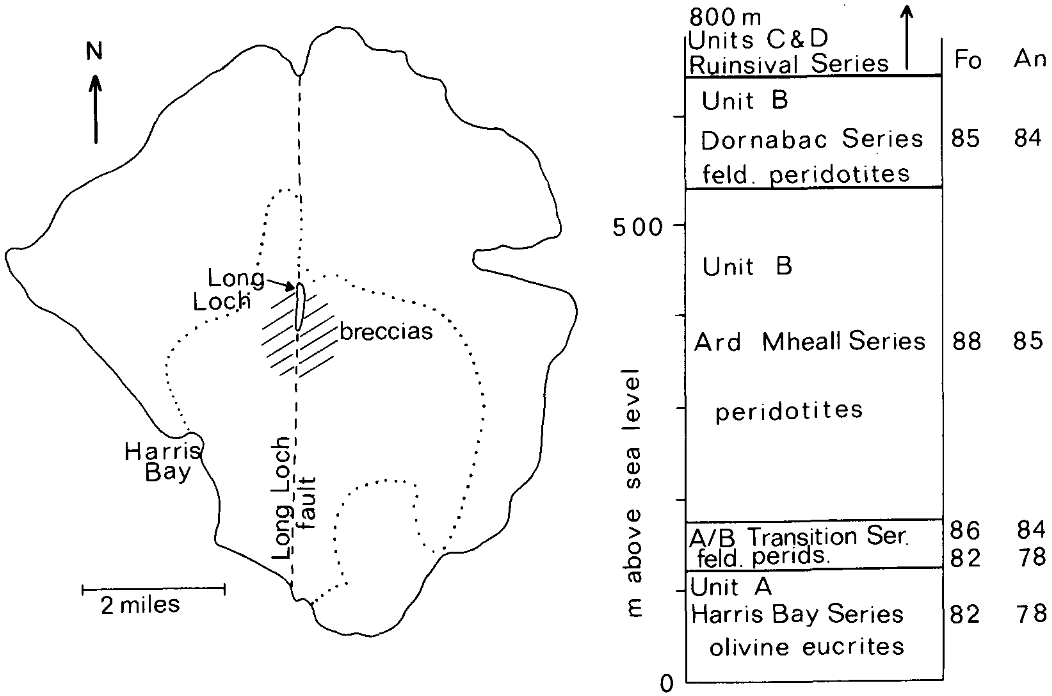

FIG. 1. Sketch map of Isle of Rhum showing principal features mentioned in text and a summary of the stratigraphy of the Western Layered Series. The layered ultrabasic rocks lie within the dotted line which is the trace of a ring fault up which the ultrabasics have been raised. The Western and Eastern Layered Series lie on either side of the Long Loch Fault. Average forsterite and anorthite contents of crystals are from Wadsworth (1961).

compositions apparently appropriate to the units they are in; for example, macro-unit A contains only olivine eucrite harrisite layers. In a more detailed investigation Donaldson (1975*a*) found that approximately 35 % by thickness of macro-unit A, 60 % of macro-unit A/B, and 20 % of macro-unit B is harrisite. The abundance of layers, combined with the lack of continuity of outcrop, renders it difficult to trace individual layers laterally for more than a few tens of metres. Layers are certainly many times longer than they are thick but the exact length is not determinable.

Harrisite is present in the Eastern Layered Series (Brown, 1956) but is scarce.

Two varieties of harrisite are common: in one there is a gradual upward change from relatively small, granular olivines in the cumulate to larger, sub-equant hopper olivines of random orientation in the harrisite and then an abrupt return to cumulate (fig. 3A); in the other variety the hopper olivines are surmounted by branching, sometimes parallel-growth-structured, olivines elongated with the *a* axis near vertical and ranging from 1 cm in length to as much as 2 m in extreme examples (fig. 3B); these branching olivines are overlain by cumulate. Rock with the oriented olivine growth structure is what Wager (1968) regarded as 'true' crescumulate; however, Wadsworth stressed that there exist all gradations from cumulate through the first variety of harrisite to the extremely elongated variety. The bases of harrisite layers are generally flat and texturally gradational, whereas the tops are sharp and may be uneven (e.g. fig. 2*d*).

Like Brown (1956), Wadsworth (1961) interpreted the layered ultrabasics of Rhum as cumulates from a differentiating basalt magma and accommodated harrisite in this scheme with the name *harrisitic cumulate.* He proposed that the rock formed during periods of magma-current stagnation, when new cumulus crystals, which he considered formed at the roof, failed to reach the floor; consequently cumulus olivine crystals already on the floor grew by removing material from super-cooled melt which had convected there. When this growth was particularly successful, olivines with their *a* axes near vertical grew most rapidly and,

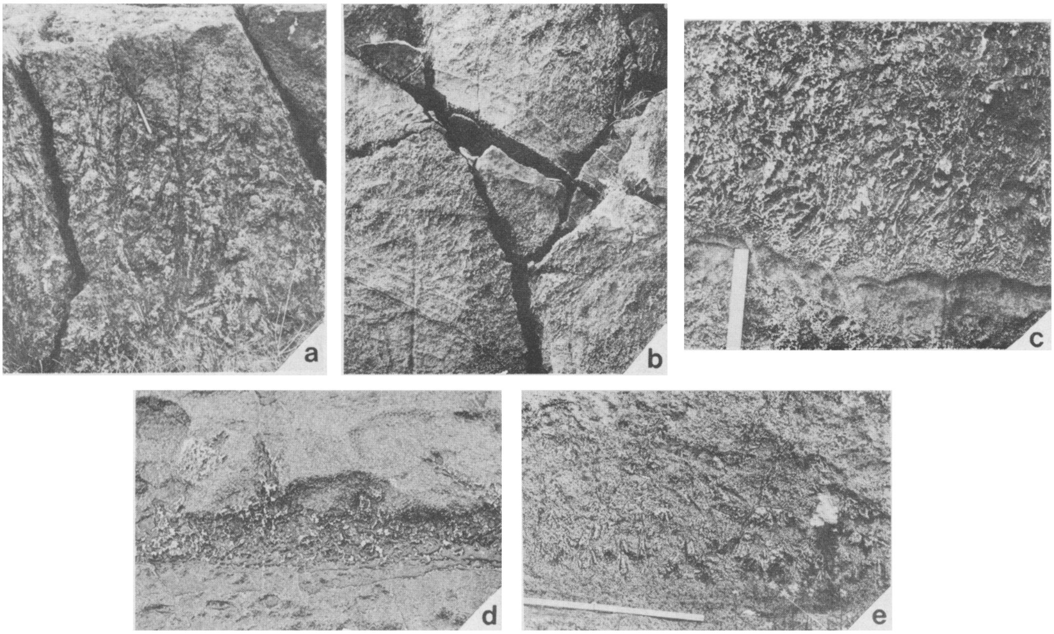

FIG. 2. Views of harrisite outcrops illustrating textural varieties. (*a*) Very long dendritic olivines branching upwards with coarse plagioclase patches and lesser augite between. (Unit A: 10 cm pencil.) (*b*) Two cycles of cumulate/harrisite, illustrating the change from fine-grained cumulate to coarse-grained harrisite with elongate olivines. (Unit A/B: height of view 2.5 m.) (*c*) Close-up of the junction between a thin cumulate layer and overlying harrisite. (Unit A/B: ruler 7.5 cm.) (*d*) Thin harrisite layer with elongate branching olivines extending into overlying cumulate. (Unit B: height of view 10 cm.) (*e*) Contact between harrisite layer and underlying cumulate—note the downward branching olivines at the base, the variety of olivine crystal shapes, and sizes in the harrisite and the absence of preferred upward growth of olivines. (Unit B: ruler 40 cm.)

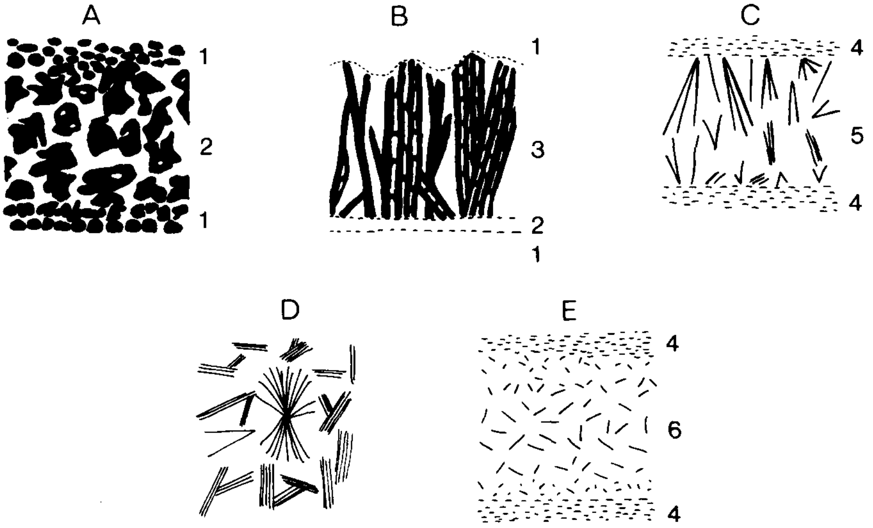

FIG. 3. Variation in textures of harrisite layers as represented by olivine shapes and orientations. Key: 1—granular olivine of cumulate; 2—hopper olivine in harrisite; 3—branching olivine of linked parallel-growth type in harrisite; 4—laminated elongate hopper olivines in harrisite; 5—branching olivines in harrisite; 6—randomly oriented elongate hopper olivines in harrisite. Vertical scales: A—5 cm; B—5 cm–1.5 m; C—0.5 m; D—30 cm; E—40 cm.

by competing with one another, ultimately developed the elongate oriented branching olivine variety of harrisite.

It was in allusion to the idea of upwardly sprouting cumulus crystals in harrisite that Wager (1968, p. 579) proposed the name *crescumulate* (crescere—Latin 'to grow or increase').

Wager *et al.* (1960) regarded harrisite as a special type of heteradcumulate in which the olivines grew from cumulus crystals, whereas the plagioclase and pyroxene nucleated *in situ* (i.e. on the floor):* being a variety of adcumulate it would have been necessary for the three minerals to have grown at the same time and approximately the same rate, with components supplied by the overlying magma. It was to this magma that Wager (1963) considered the latent heat of crystallization was transferred, ultimately to be lost through the roof of the chamber, when the magma had convected there.

In summary, Wadsworth's observations of harrisite seem consistent with the distinctive variety of rhythmic layering having formed *contemporaneously* with the contiguous cumulate—after the layer below and before the one above.

Harrisite with atypical features

For some years this author has investigated textural aspects of harrisite: the olivine crystal shapes and their patterns of variation; the amount of supercooling necessary to cause crystallization of skeletal and dendritic olivines; the cause of the supercooling; and the reasons why comb layering developed in some of the layers (Donaldson, 1974, 1975*a*, 1976, 1977; Lofgren and Donaldson, 1975). During these investigations he too believed that all harrisite formed contemporaneously with cumulate: however, recent detailed field observations of the rock type, outlined below, suggest a different conclusion for some harrisite.

1. Wadsworth (1961) noted that individual harrisite layers may change in thickness along strike due to projection of individual olivines or 'reefs' of olivine into the overlying cumulate; this change is rarely more than 10% of the average thickness of the layer. However, there are layers in which thickness varies along strike by 30–90% of the average value. Some layers have even been observed to narrow, terminate, and then reappear some 0.5 to 4 m along strike, the gap being occupied by cumulate.

2. Conversely, there are occurrences in which a cumulate layer terminates against harrisite and reappears some distance along strike. One, in macro-unit A/B, involves a 15 cm-thick cumulate layer which has a 3 m-wide break occupied by harrisite; as the cumulate layer is both underlain and overlain by harrisite, its parts appear to be engulfed in harrisite. Another example in macro-unit A involves two harrisite layers, both approximately 30 cm thick, separated by a 60 cm-thick cumulate layer; in one outcrop an inclined 0.5 m-wide harrisite 'dyke' cuts through the cumulate, to connect the two harrisite layers. The margins of the 'dyke' are neither chilled nor are they sharply clear-cut, the skeletal crystals merely give way gradually to the granular ones of the cumulate.

3. Numerous examples exist of thin isolated lensoid masses of harrisite. Most are flattened and elongated approximately in the plane of rhythmic layering, but one lens (fig. 4) has split into two parts, the lower part being distinctly inclined to the layering plane. A similar type of occurrence consists of a series of isolated, sub-spherical pods of harrisite, from 10 to 20 cm across, bearing no obvious relation to the layering plane.

4. Several examples have been found of tongues and round lobes of harrisite (from 0.1 to 1 m across) extending up from a harrisite layer into the overlying cumulate (fig. 5*a* and *b*). Where the overlying cumulate is layered, the layering is locally convexly curved over the tongue (fig. 5*b*). These occurrences are quite different from the individual crystals of skeletal or dendritic olivine which Wadsworth (1961) noted penetrating cumulate layers (e.g. fig. 2*a*). In one such lobe-shaped mass (fig. 5*c*) the outermost elongate olivines of the lobe are radially arranged (i.e. approximately at right angles to the lobe–cumulate boundary), suggesting that the boundary existed prior to crystallization of the elongate olivines in the harrisite.

5. A few outcrops contain a harrisite layer gradually 'dying out' along strike as it passes into normal cumulate texture; i.e. the grain size

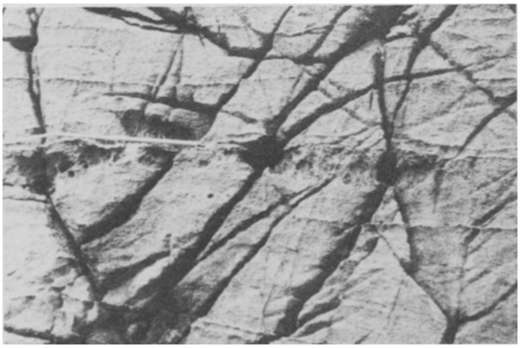

FIG. 4. Lens of harrisite in cumulate. Unit A: ruler 0.9 m. Note the 'split' in the harrisite at the left-hand end.

---

* Except in some of the unit A harrisite in which Wadsworth felt that olivine and plagioclase were cumulus phases.

decreases and the skeletal olivines give way to granular ones.

6. In various places, 1-3 cm-thick layers of harrisite and cumulate interdigitate on a small scale (< 20 cm) though remain essentially conformable with the overall layering.

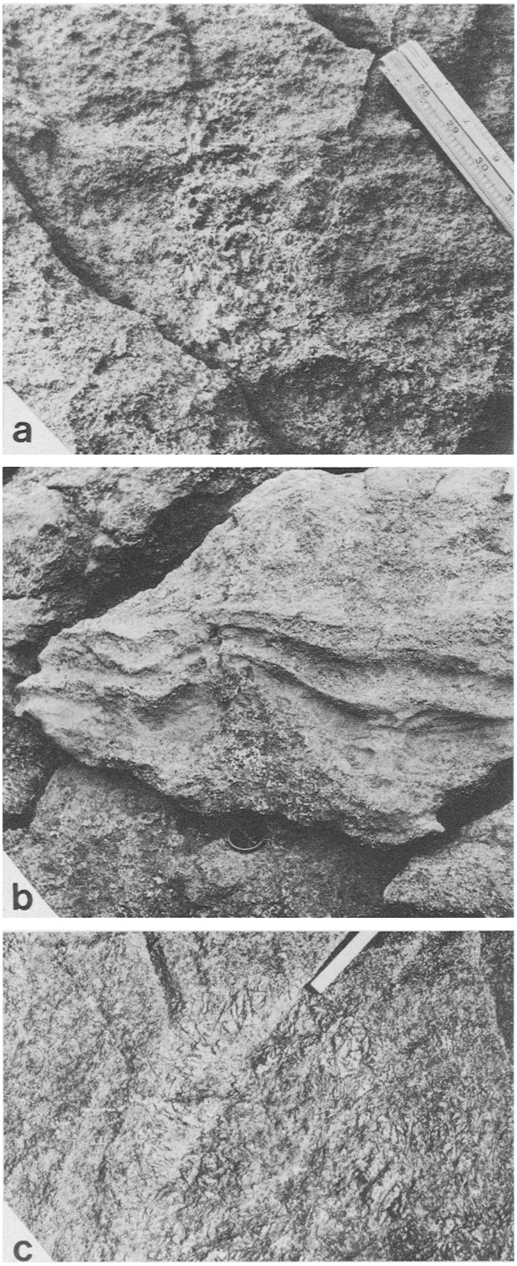

FIG. 5. Tongues of harrisite extending into overlying cumulate. (*a*) Unit A: ruler 22 cm. (*b*) Unit B. (*c*) Unit A: ruler 25 cm.

7. The western contact between layered ultrabasic and granophyre is well exposed on the beach at Harris Bay, and it is clear that the horizontal banding in the ultrabasic persists right up to the contact, despite the contact being a fault along which the ultrabasics were uplifted relative to the granophyre (Wadsworth, 1961). At places along the contact are discontinuous masses of eucritic harrisite, from 0.5 to 2.5 m across, most having randomly oriented elongate hopper olivines; some masses are elongate parallel to the contact and are of irregular outline, others are diffuse patches, and yet others are sub-spherical, with large elongate olivines radiating outwards from their centres to margins. All these masses have diffuse rather than sharp contacts with the enclosing cumulate. There is no indication that they formerly were a single layer; on the contrary, each seems to have crystallized in place.

8. In the same area a thick harrisite layer (~ 4 m), when traced along strike towards the contact, is replaced by three layers of harrisite ranging from 8 to 30 cm thick separated by cumulate layers. Though outcrop is absent where the thinner layers and the thick layer must meet, apparently the thick layer splits into a number of thinner ones.

9. North of Loch Dornabac, on either side of the Long Loch Fault ultrabasic breccias abound (fig. 1). These are currently under detailed investigation by Miss J. McClurg but seem to resemble the nearby breccias described by Wadsworth (1961) and Donaldson (1975*b*). Blocks of cumulate and harrisite are enclosed in peridotite matrices which are texturally indistinguishable from cumulate. The Long Loch breccias are interesting in the present context because in a few localities an isolated patch of matrix has harrisite texture (fig. 6), i.e. the

FIG. 6. Patch of harrisite-textured matrix in the peridotite matrix of an ultrabasic breccia west of the Long Loch fault. Width of view 25 cm.

olivines are coarser than those in the bulk of the matrix and they have skeletal shapes (they are not, however, preferentially oriented). The diffuseness of the cumulate–harrisite boundary distinguishes these pods from blocks of harrisite incorporated in the breccia.

10. The present study found that while most harrisite layers have hopper or hopper and branching olivines disposed in the manner shown in fig. 3A and B, there are additional olivine shapes and patterns of shape variation which occur in the intrusion (Donaldson, 1974). These include radiate olivines, elongate hopper olivines, branching olivines which have grown upwards or downwards or horizontally, and randomly oriented elongate hopper olivines which are coarsest in the centre of a layer and become smaller towards both the top and bottom of the layer, where they are aligned parallel to the layer contacts (fig. 3C, D, E).

Location of harrisite crystallization

The comments in the previous section concern less than 10% of all harrisite. Most harrisite, including all comb-layered harrisite, has features consistent with the olivines having grown at the top of the crystal mush, before formation of the next cumulate layer. Whether or not the olivines grew from settled (i.e. cumulus) crystals (Wadsworth, 1961) or nucleated *in situ* (Donaldson, 1977) the essence of the crescumulate hypothesis, namely growth of the large skeletal-dendritic olivines *in situ* while at the mush–magma junction is compatible with the field evidence.

On the other hand, for the small proportion of layers, lobes, and lenses described in the previous section it seems necessary that the overlying cumulate existed *before* crystallization of the harrisite; for example, the presence of harrisite pockets in the matrices of the breccias, the trains of harrisite pods along the ultrabasic–granophyre contact, the olivines which apparently grew downwards in some harrisite (e.g. fig. 3C) and the lobe with radiating olivines. Others of the features described (numbers 1–6 and 8), while not refuting crystallization at the mush–magma junction, are more reasonably attributed to mobility of the harrisite-forming melt *within* the mush.

Therefore it is suggested that a small proportion of harrisite owes its origin to the ability of melt to collect within the mush as pods, sheets, and lenses, with subsequent skeletal-dendritic olivine crystallization.

This is not a new proposition; it was espoused by Harker (1908) (and apparently by Drever and Johnston, 1972) who regarded all harrisite as a late-stage pegmatite injected along planes of weakness in the cumulates. The extremely coarse grain size of some harrisite and the generally much larger content of hydrous minerals in harrisite compared to cumulate (Wadsworth, 1961) led Harker to this view.

Petrogenesis of harrisite within cumulate mush

Suggested mechanism of intercumulus melt segregation. Although Harker (1908) applied the term 'pegmatite' to harrisite he did not indicate where he believed the source of the pegmatite melt-fluid to be. For lack of evidence to the contrary, I assume that he considered it to be H_2O-enriched melt residual from the crystallization of individual rhythmic layers, each of which he regarded as a separate intrusive sill.

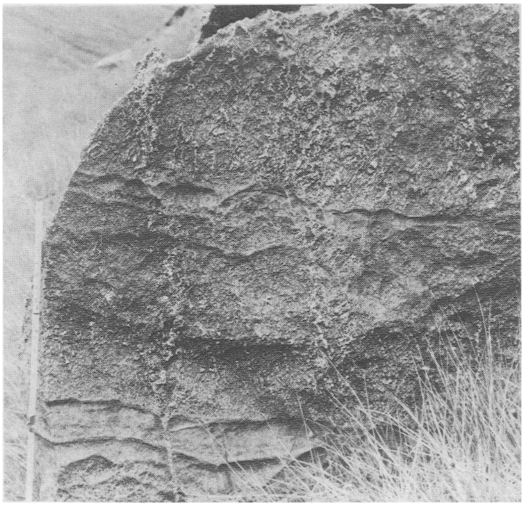

FIG. 7. Vertically aligned feldspathic veins cutting both cumulate and harrisite layers. (Unit A/B: ruler 90 cm.)

It is established that the Rhum layering is the result of progressive upward solidification of magma in a shallow-level chamber which was repeatedly refilled with batches of mafic magma, each of which gave rise to a single macro-unit of rocks (Wager and Brown, 1968). In the chamber at any time there existed magma overlying a porous crystal–liquid mush and the porosity diminished downwards to zero at some depth, below which the mush was completely solidified. This depth exceeded 6 m (Wadsworth, 1961) and may well have been many times this value, if Hess's (1973) treatment of consolidation of the Stillwater intrusion is extendable to Rhum.

By analogy with terrigenous sediments, intercumulus melt in the mush might migrate in two ways: by upward percolation through the mush as a result of compaction of the ever-thickening sediment pile (cf. Irvine, 1978), and by mass release of melt from some level within the mush (cf. the 'fluid-escape structures' of terrigenous sediments (Blatt *et al.*, 1980, p. 185), examples of which exist in the Bushveld intrusion (Lee, 1981, fig. 4B). That intercumulus melt did migrate within the Rhum mush is clearly shown by the abundance of veins and stringers of anorthositic gabbro in the cumulates (e.g. fig. 7).

However, in order for the migrating melt to accumulate in layers, lenses, and pods, it is necessary to postulate non-uniform permeability of intercumulus melt in the mush, such that in places the melt was able to collect beneath relatively impermeable cumulate layers. Differences in permeability would arise from variations in size, shape, and packing of cumulus crystals, preferred orientation of cumulus crystals (e.g. igneous lamination), extent of intercumulus crystallization, tortuosity of the channels between cumulus crystals and porosity* (e.g. Spera, 1980). Ascending melt would tend to 'pond' beneath relatively impermeable mush, in a manner similar to that described by Fyfe *et al.* (1978, pp. 285–99) for formation of 'water sills' in a developing sedimentary basin. To form a layer of melt beneath a layer of relatively impermeable cumulate mush requires that the underlying melt develop a small fluid overpressure and also that the layer of overlying mush be strong enough to resist fracture. Should the relatively impermeable layer of mush subsequently rupture, the ponded melt would penetrate it as a small diapir.

The point was made in the field description (number 8) that at least one thick layer probably splits laterally into numerous smaller ones. Thus some harrisite layers almost certainly were capable of propagating laterally, probably by lateral movement of melt in a sill-like injection.

Whereas the physics of terrigenous sediment compaction and fluid permeability has been investigated for many decades, that in igneous sediments has largely been ignored (Hess, 1973, being a notable exception). This is likely to be remedied soon, as those who have been mathematically modelling the segregation of partial melt in magmatic source regions turn their attention to cumulate mushes (e.g. Walker *et al.*, 1978; Waff, 1980; Spera, 1980; Maaloe, 1981; Stolper *et al.*, 1981).

Differentiation in harrisite. Some of the harrisite under discussion has an olivine content exceeding 40 vol.% and must be regarded as a differentiate of a less olivine-rich magma, even though it has been argued that the Rhum parent magma was normatively rich in olivine (Donaldson, 1977). If some harrisite did indeed crystallize in the way envisaged above, there must have been some flow of melt through the relatively impermeable layer overlying harrisite, such that melt depleted in olivine by the crystal growth in the developing harrisite could be removed from the 'pond' and be replaced by more olivine-rich melt from below (i.e. the process of 'infiltration metasomatism' of Irvine, 1978). This conclusion is also necessary to explain how latent heat of crystallization was removed from the 'harrisite layer', because if it were not, crystallization would soon have stopped (see also next section).

The supersaturation problem. Any crystallization scheme for harrisite faces the fact that the skeletal and dendritic crystals grew under enhanced supersaturation conditions (e.g. Saratovkin, 1959) which caused them to enlarge up to ten times more rapidly than the cumulus crystals (Henderson and Williams, 1979). Experimental work by Donaldson (1976, 1977) has determined values of supercooling (ΔT) and of cooling rates at which various shapes of olivine crystal will grow in magmas; it was found that, whereas the ΔT's at which various shapes grow are insensitive to melt composition, the cooling rates at which particular shapes grow are dependent on the olivine content of the melt concerned; thus the larger the olivine content of the melt, the slower need it be cooled to form skeletal and dendritic shapes. Cooling rates $< 0.1°/\mathrm{h}$ and values of ΔT from 10 to at least 30° would have produced the olivine crystals in harrisite layers. The petrologic problem is to account for this supercooling. Four causes can be imagined:

1. The migrating melt had a lateral component of motion towards the intrusion margin and cooled as it moved there.
2. The migrating melt blended with more refractory melt and, since both melts are saturated with olivine and the olivine liquidus is convex upwards in T–X space, the blend is more supercooled (cf. Walker *et al.*, 1979).
3. As the melt collected in pools, nucleation of olivine may have been inhibited and delayed compared to that occurring in the overlying magma because shearing motion, which is known to stimulate nucleation (Chalmers, 1964), was slight or absent.
4. The liquidus slopes of anhydrous and water-undersaturated magmas in P–T space are positive, such that ascending magma will superheat rather than supercool until it becomes supersaturated

---

* Spera's treatment suggests that doubling porosity increases melt flow rate by a factor of twenty.

with water. Conversely an ascending water-saturated magma will supercool. dT/dP of the liquidus of water-saturated basalt ranges from $-90°$/kbar ($-0.03°$/m) at $P < 0.5$ kbar to $-15°$/kbar ($-0.005°$/m) at $P > 2$ kbar (estimated from fig. 27 of Yoder and Tilley, 1962). Water-saturated magma will also cool as a result of adiabatic expansion of exsolving water; fig. 4.5 of Williams and McBirney (1979) indicates that a magma plus vapour mixture cools by 0.1° for every metre it ascends. Whether the intercumulus melt which crystallized as harrisite was saturated with water is a matter of conjecture but two features are consistent with this possibility: kaersutite and phlogopite are primary phases in the Rhum cumulates and these minerals and other, secondary, hydrous minerals are abundant in the harrisite (up to 15% of rock); and the exposed Rhum cumulates are of the order of 1000 m thick (Emeleus and Forster, 1979) and have been uplifted by a maximum of 1000 m (Dunham and Emeleus, 1967). The lithostatic pressure in macro-units A, A/B, and B therefore would have been about 0.6 kbar and less than 2 wt.% water would have saturated the melt (Williams and McBirney, 1979, fig. 2.13). In addition, it is well established that other British Tertiary intrusions exchanged oxygen with meteoric water circulating around the plutons (Taylor and Forester, 1971), and it is certain that the same occurred on Rhum; I suggest that some meteoric water may have dissolved in intercumulus melt, adding to its water content. The chances therefore seem good that water-saturated melt was present in the mush of macro-units A, A/B, and B, though the magma overlying the mush was most likely undersaturated. If so, then melt ascending through, for example, 100 m would cool by approximately 10°, assuming the unlikely possibility that it did not crystallize during ascent, or that it ascended very rapidly.

However, it is doubtful that any of these mechanisms, singly or collectively, could have supercooled the intercumulus melt by as much as the 30° which the experiments synthesizing olivine crystal shapes imply. There seem to be three ways of resolving this impasse, none of which is obviously the correct explanation:

1. The values of ΔT obtained from the experiments are too high. In other experiments Donaldson (1979) showed that accurate location of the olivine liquidus temperature may readily be overestimated by 10–20 °C. If this happened in the experiments investigating olivine morphology, then ΔT values of 10–20° less than those reported by Donaldson (1976) would be appropriate. Another possible source of error in the experiments lies in the fact that they were conducted on sealed capsules of melt representing a closed system, whereas harrisite crystallized under open-system conditions in which the olivine content of the melt probably remained uniform and high throughout olivine crystallization, thereby helping to sustain rapid growth.

2. The late H. I. Drever brought to my attention that pods of gabbroic pegmatite in various Scottish Tertiary intrusions often contain large skeletal olivines accompanied by plagioclase, pyroxene, and hydrous minerals; a reasonable inference is that as water builds up in residual basic melts (or water dissolves in them) so olivine supersaturation is usually enhanced. This effect could come about if the liquidus slope in T–X space becomes flatter with water addition (cf. Wyllie, 1963; Donaldson, 1974). Data to test this possibility at low pressure do not exist, though at 20 kbar it is true in the forsterite–silica system (Kushiro, 1969).

3. The possibility that the process of double-diffusive convection might occur in magma chambers and contribute to the development of igneous layering has recently upset the cumulate applecart. As noted by Irvine (1980) this process is a very efficient means of removing heat from the mush–magma interface. However, Turner and Gustafson (1978) indicate that the process could equally well occur in a fluid in a porous medium. Perhaps this is how heat was removed from within the Rhum mush to encourage rapid olivine crystallization in harrisite lenses and pods, etc.

In summary, the supersaturation conditions involved in harrisite crystallization remain enigmatic: the high level of the intrusion together with access of meteoric water to the chamber may be critical conditions. However, it is probable that previous estimates of the necessary supercooling err on the large side and also that temperature variation during crystallization of olivine in harrisite layers may have been < 15 °C.

A possible alternative explanation. During a field excursion in 1980, T. N. Irvine suggested that harrisite might represent cumulus olivine crystals which recrystallized into larger skeletal and dendritic ones within the mush. Irvine has invoked recrystallization to explain replacement of pyroxene by olivine under the influence of H_2O-rich vapour in the Duke Island complex (Irvine, 1974) [cf. Loomis and Gottschalk, 1981]; he has also proposed that meteoric water entered intercumulus melt in the Skaergaard intrusion and that pockets of this melt caused recrystallization of cumulate to coarse-grained anorthosite (Irvine, 1980). As an explanation of harrisite formation, recrystallization disposes of the supercooling problem, the need for both differentiation within the mush and for the creation of space for melt to accumulate in the mush. What is not obvious is why recrystallization might result in layers with such clearly defined contacts, in stratification with respect to olivine crystal shape and size, and in more than one variety of harrisite texture. Consequently I still cling to the belief that the olivines in harrisite crystallized directly from supercooled melt. Irvine's suggestion is not refutable; in fact it highlights the need for experiments to simulate the post-cumulus 'diagenesis' of cumulate mushes to examine the possible textural changes that may occur.

Conclusion

It has been argued that whereas most harrisite probably did crystallize at the mush-magma boundary, as the crescumulate hypothesis advocates, some harrisite crystallized within the mush. This latter variety is believed to be a differentiate of upward-moving intercumulus melt which collected beneath layers of low permeability in the mush. The cause of the supersaturation is inadequately understood, but its continuance during harrisite crystallization was responsible for differentiation.

The mechanism proposed here is, in effect, one of filter pressing; it is worth noting that although filter pressing has been invoked to explain the features of many intrusions (see Propach, 1976, for review), it has been neglected as a process operating in layered intrusions, despite its inevitability due to sediment compaction. The proposition that upwardly percolating melt may 'segregate' to form discrete layers has been recognized in Rhum because the resultant rock type is texturally radically different from the contiguous ones. If further work bears out this conclusion, it will be worth considering whether other layers in cumulate sequences might also have such an origin—a possible candidate might be the 'uniform gabbro layers' of the Skaergaard intrusion (Wager and Deer, 1939), or the peridotite-anorthosite banding in the Garbh Bheinn intrusion (Weedon, 1960).

Acknowledgements. I thank W. J. Wadsworth, J. Elder, I. Young, and an anonymous reviewer for their helpful reviews of an earlier version of the manuscript.

REFERENCES

Blatt, H., Middleton, G., and Murray, R. (1980). *Origin of Sedimentary Rocks.* Prentice-Hall, New Jersey.

Brown, G. M. (1956) *Phil. Trans. R. Soc.* **B240,** 1-53.

Chalmers, B. (1964) *Principles of Solidification.* Wiley, New York.

Chen, C. F., and Turner, J. S. (1980) *J. Geophys. Res.* **85,** 2573-93.

Donaldson, C. H. (1974) *Geol. Soc. Am. Bull.* **85,** 1721-6.

——(1975*a*) Unpubl. Ph.D. thesis, Univ. St. Andrews.

——(1975*b*) *J. Geol.* **83,** 33-45.

——(1976) *Contrib. Mineral. Petrol.* **57,** 187-213.

——(1977) *Mineral. Mag.* **41,** 323-36.

——(1979) *Contrib. Mineral. Petrol.* **69,** 21-32.

Drever, H. I., and Johnston, R. (1972) *Meteoritics,* **7,** 327-40.

Dunham, A. C., and Emeleus, C. H. (1967) *Proc. Geol. Assoc.* **78,** 391-418.

Emeleus, C. H., and Forster, R. M. (1979) *Field Guide to the Tertiary Igneous Rocks of Rhum, Inner Hebrides.* Nature Conservancy Council.

Fyfe, W. S., Price, N. J., and Thompson, A. B. (1978) *Fluids in the Earth's Crust.* Elsevier, Amsterdam.

Harker, A. (1908) *Mem. Geol. Surv. Scotland.*

Henderson, P., and Williams, C. T. (1979) In *Origin and Distribution of The Elements* (Ahrens, L. H., ed.), Pergamon, London.

Hess, G. B. (1973) In *Studies in Earth and Space Sciences* (Shagam, R., ed.), Geol. Soc. Am. Mem. 135, 503-20.

Huppert, H. E., and Turner, J. S. (1981) *J. Fluid Mech.* **106,** 299-329.

Irvine, T. N. (1974) *Geol. Soc. Am. Mem.* 138.

——(1978) *Geophys. Lab. Yearb.* **77,** 743-51.

——(1980) In *Physics of Magmatic Processes* (Hargraves, R. B., ed.), Princeton Univ. Press, Princeton, NJ.

Kushiro, I. (1969) *Geophys. Lab. Yearb.* **67,** 158-161.

Lee, C. A. (1981) *J. Geol. Soc.* **138,** 327-41.

Lofgren, G. E., and Donaldson, C. H. (1975) *Contrib. Mineral. Petrol.* **49,** 309-19.

Loomis, T. P., and Gottschalk, R. R. (1981) Ibid. **76,** 1-11.

Maaloe, S. (1981) *J. Geol. Soc.* **138,** 223-36.

Propach, G. (1976) *Lithos,* **9,** 203-9.

Rice, A. (1981) *J. Geophys. Res.* **86,** 405-17.

Saratovkin, D. D. (1959) *Dendritic Crystallization.* Consultant's Bureau, New York.

Spera, F. J. (1980) In *Physics of Magmatic Processes* (Hargraves, R. B., ed.), Princeton Univ. Press, Princeton, NJ.

Stolper, E., Walker, D., Hager, B. H., and Hays, J. F. (1981) *J. Geophys. Res.* **86,** 6261-72.

Taylor, H. P., and Forester, R. W. (1971) *J. Petrol.* **12,** 465-97.

Turner, J. S., and Gustafson, L. B. (1978) *Econ. Geol.* **73,** 1082-1100.

Wadsworth, W. J. (1961) *Phil. Trans. R. Soc.* **B244,** 21-64.

Waff, H. S. (1980) *J. Geophys. Res.* **85,** 1815-25.

Wager, L. R. (1963) *Spec. Paper Mineral. Soc. Am.* **1,** 1-9.

——(1968) In *Basalts* (Hess, H. H., and Poldervaart, A., eds.), Interscience, New York.

——and Brown, G. M. (1968) *Layered Igneous Rocks.* Oliver & Boyd, Edinburgh.

——and Deer, W. A. (1939) *Meddels. Grønland,* **105,** 1-352.

——Brown, G. M., and Wadsworth, W. J. (1960) *J. Petrol.* **1,** 73-85.

Walker, D., Stolper, E. M., and Hays, J. F. (1978) *J. Geophys. Res.* **83,** 6005-13.

——Shibata, T., and De Long, S. E. (1979) *Contrib. Mineral. Petrol.* **70,** 111-25.

Weedon, D. (1960) *Q. J. Geol. Soc.* **116,** 37-54.

Williams, H., and McBirney, A. R. (1979) *Volcanology.* Freeman Cooper, Los Angeles.

Wyllie, P. J. (1963) *Spec. Paper Mineral. Soc. Am.* **1,** 204-12.

Yoder, H. S., and Tilley, C. E. (1962) *J. Petrol.* **3,** 342-532.