Laboratory duplication of comb layering in the Rhum pluton

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SUMMARY. The changes in olivine morphology and grain size upwards through comb-layered olivine eucrite and peridotite varieties of harrisite in the Rhum layered pluton are systematic, from abundant small granular crystals, to fewer and larger hopper crystals, to highly elongate branching crystals, which are preferentially elongate along the a axis and perpendicular to the plane of the layering. These changes have been reproduced in the laboratory by cooling water-bearing melts ($P = 5$ kb) of harrisite at 14 and 30 °/hr. These cooling rates represent maximum values for natural crystallization of comb-layered harrisite. Other experiments suggest that the oriented branching olivines in the rock crystallized at 30–50 °C supercooling. The results indicate that continuous, rather than abrupt, changes in the degree of supercooling and supersaturation of the magma can cause formation of comb layers. They also indicate that while field relations point to growth of most comb layers along a thermal gradient in the magma, this is not an essential condition for comb layer formation. Growth could be along a compositional gradient instead. During crystallization of a comb layer, both nucleation rate and the number of crystals suspended in magma close to the layer are essentially zero. Conditions initiating and terminating comb layer formation and the origin of the rapid vectorial crystallization are discussed. It is suggested that some comb layers could form without change in degree of supercooling, due to rapid removal of crystals suspended in the magma causing the enhanced growth rate and branching style of growth of the remaining crystals. Multiple origins of comb-layered rocks may therefore be possible.

CURRENTLY, most layered igneous rocks are considered to form by gravity sorting and accumulation of crystals (e.g. Jackson, 1971). On the other hand, the origin of layers containing vectorially oriented crystals, variously known as 'comb layers', 'Willow Lake layers', and 'crescumulate layers', has not been convincingly elucidated. These layers are generally ascribed to *in situ* crystallization under enhanced supercooling conditions (e.g., Taubeneck and Poldervaart, 1960). However, the mechanism by which the magma supercools has not been discussed with confidence, principally because, without knowledge of the degree of supercooling, it is impossible to estimate the magnitude, and hence feasibility, of the possible physical-chemical changes that could cause supersaturation and crystallization.

Lofgren and Donaldson (1975) partially remedied this problem by determining the degrees of supercooling (ΔT) and the cooling rates at which branching plagioclase crystals, typical of those in comb-layered rocks, grew in the laboratory. They crystallized synthetic feldspar–water melts and stressed that these ΔT's and cooling rates were probably maximum possible values for natural magmas.

Some of the layered 'harrisitic' rocks (harrisite) of the Isle of Rhum pluton contain elongate branching olivines preferentially oriented perpendicular to the plane of the layering (Harker, 1908; Wadsworth, 1961; Wager and Brown, 1968; Donaldson, 1974) and identical to the texture of comb layers (fig. 1). The abundance of well-exposed harrisite layers in Rhum provides a unique opportunity for detailed examination of comb layering.

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This paper describes the texture of harrisite comb layers and illustrates the results of crystallization experiments at controlled cooling rates, which have reproduced the textural change from 'cumulate' to comb-layered harrisite. Melted samples of harrisite were used in these dynamic crystallization experiments and, since one of the samples had a composition similar to that postulated for the parent magma of harrisite (Donaldson, 1975a, b), some of the results are directly applicable to harrisite petrogenesis and to the origin of comb-layered harrisite. The experiments also indicate ways in which comb layer formation is initiated and why the crystal growth is vectorial.
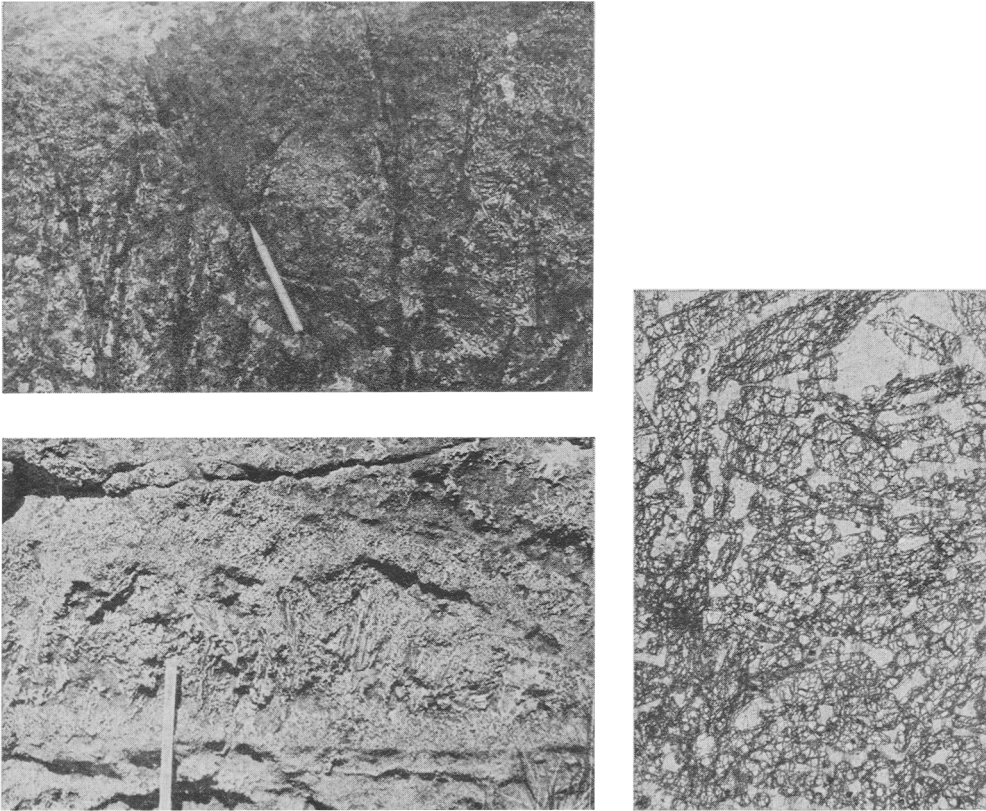
FIGS. 1 and 2: FIG. 1 (top left). Comb-layered harrisite displaying preferred vertical elongation of olivines. Pencil is 10 cm long. (Harris Bay Series.) FIG. 2a (bottom left). Layer of harrisite illustrating the change from underlying cumulate to *hopper* olivine to elongate *branching* olivine. Ruler is 20 cm long. (Transition Series.) FIG. 2b (right). Thin section of the gradational contact between peridotitic cumulate (base) and overlying peridotitic harrisite. Field of view is 2 cm wide. (Ard Mheall Series.)

Nomenclature of layered rocks containing skeletal and branching crystals. Independent investigations of layered igneous rocks containing oriented branching crystals inevitably resulted in a diverse nomenclature involving descriptive, geographic, and also genetic terms. The result is to obscure the genetic relation of layering in different igneous bodies. Four frequently used terms are: 'Willow Lake layering' (Taubeneck and Poldervaart, 1960), 'comb layering' (Moore and Lockwood, 1973), 'harrisitic layering' (Wager and Brown, 1951), and 'crescumulate layering' (Wagner, 1968). Of these terms, 'comb-layering' is most satisfactory in being descriptive and having no genetic connotation. I therefore propose that the other terms be dispensed

with as indicators of preferred orientation of elongate skeletal crystals. I also propose that more accurate description of comb layers can be achieved by stating the elongate skeletal mineral or minerals oriented, e.g., 'branching olivine comb layer' would specify a layer with elongate branching olivines preferentially oriented nearly perpendicular to the plane of the layer.

'Harrisite' can usefully be retained as a petrologic term, for which the following definition, based on field, mineralogic, and textural criteria, is suggested (Donaldson, 1975a). 'Harrisite is an ultrabasic, plutonic igneous rock in layered intrusions which contains > 25 vol. percent of olivine. The olivine crystals are characterised by skeletal or dendritic shapes and have larger size than euhedral–subhedral, non-skeletal olivines in contiguous layers.' Those harrisite layers that contain elongate olivines oriented approximately perpendicular to the layer boundaries can adequately be distinguished as 'comb-layered harrisite'.

Textural 'anatomy' of comb-layered harrisite. There is a consistent, systematic pattern of change in shape and abundance of olivine crystals upwards from cumulate into comb-layered harrisite. Small, equant, round, *granular*[1] olivines (figs. 2a, b and 3) in the cumulate are overlain by progressively larger and more deeply indented olivines. A further upward change in olivine shapes is the development of internal (hollow) skeletal structure, in addition to the indented skeletal shape. At this level, olivines are *hopper* skeletons (figs. 2b and 3). Further upward change of shape is marked by the presence of very large, parallel-growth and *branching* olivines, which are elongate along the *a* crystallographic axis (Wadsworth, 1961), and in some layers are preferentially vertically elongate (fig. 2a). These elongate crystals often terminate in euhedral {110} prisms. Grain size and abundance of olivines vary insignificantly above the level at which the olivines become of branching type. Hence, a gradational change in olivine morphology and texture is common within many harrisite layers, as cumulus crystals give way to larger olivines, which are vectorially oriented in some layers. The change involves a decrease in number of olivine crystals by up to a factor of $1/1500$ and a grain size increase of up to 1000 times.

Gradational change in olivine morphology upwards from cumulate to harrisite is also shown by Drever and Johnston (1972, fig. 5a). Underlying the skeletal olivines in the harrisite are elongate, tabular, *polyhedral* olivines with prominent horizontal foliation (*b* perpendicular to the layer). Upwards, the tabular olivines are indented and less markedly tabular and foliated. The complete upward morphology change involves: foliated tabular *polyhedral* olivine → foliated, indented, tabular *polyhedral* olivine → unfoliated, weakly tabular *polyhedral* olivine → unoriented *hopper* olivine → *branching* olivine, vertically elongate and forming a comb layer. The interval between the first and the last of these changes is approximately 6 cm. These changes suggest a gradual transformation from conditions of crystal settling to dominantly *in situ* crystallization of *branching* olivine.

The upward change from abundant, small, *granular* or *polyhedral* olivines to *hopper* olivine to *branching* olivine (fig. 3) is observed in many layers. The relative position and grain size of different olivine morphologies within a layer does not vary, only the thicknesses of rock units containing olivine of each shape. Also, the skeletal olivines in some harrisite layers may be only of *hopper* type, *branching* olivine being absent. These observations indicate *gradual* change from equilibrium to non-equilibrium crystallization.

The upper contact of harrisite with cumulate is abrupt in texture and grain size (fig. 3). Whether recommencement of settling of cumulus crystals terminated comb layer formation, or whether harrisite formation had ceased before deposition of the cumulate, is indeterminate. Intimate mixing of the two rock types at the top of layers favours the former possibility.

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[1] The names in italics indicate different shapes of olivine crystals and are taken from the classification scheme of Donaldson (1976).

The descriptions of rocks in the Willow Lake Intrusion (Taubeneck and Poldervaart, 1960, p. 1306) indicate that the change from granodiorite to comb-layered granodiorite also involves a textural change from abundant small granular crystals to fewer, skeletal branching crystals elongated at high angles to the banding.
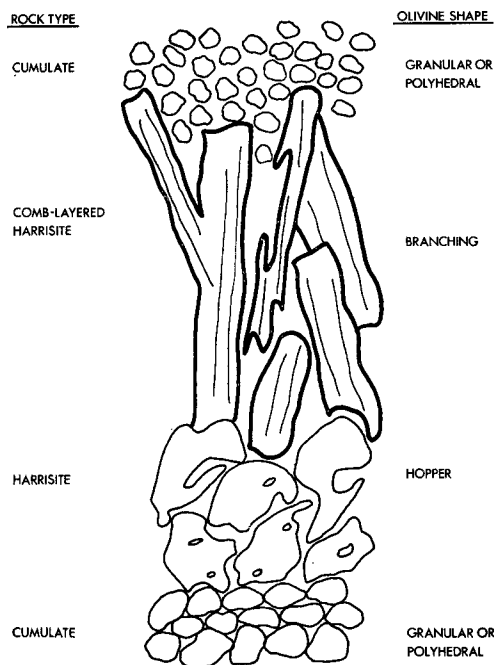

FIG. 3. Generalized sketch of the changes in olivine crystal shape and grain size distribution associated with comb-layered harrisite. Space between olivines is occupied by plagioclase and pyroxene.

Experimental duplication of comb-layered harrisite

Method. Donaldson (1976) described the results of crystallization experiments on mafic and ultramafic melts that showed systematic changes in shapes of olivine crystals with degree of melt supercooling and with cooling rate. One melt investigated was an olivine-eucrite variety of harrisite (sample E, Table I), similar in composition to a magma postulated to be parental to the Rhum intrusion (Donaldson, 1975b). Two other samples are peridotite varieties of harrisite (samples A and F, Table I). Powdered sample was loaded together with excess water into a platinum capsule (15×3 mm), which was crimped and welded. The charges were totally melted at 5 kb and 1250 °C (20 to 75 °C above the liquidus) for 2 hours and then either rapidly cooled to a crystallization isotherm, or cooled to the solidus at constant, controlled rates of 2–130°/hr (Donaldson, 1976). Care was taken to ensure that the flattened plane of the capsule was vertical. The run products are olivine and fine-grained amphibole.

Results. Certain of the controlled cooling rate runs (at 14, 28, and 30°/hr) display morphological, as well as compositional, differentiation in the run products. A layer of *granular* olivine occupies the base of the charge and is covered by *hopper* olivine (fig. 4), itself covered by *branching* olivine. The change from *granular* olivine to *hopper* olivine is gradational, involving an increase in grain size and crystallization of less round, and more inlaid, olivines.

Only a few isothermal runs display these differentiation features, and usually much less dramatically than do cooling rate runs. The differentiated charges are layered according to olivine morphology and relative grain size in a manner identical to harrisite layers. For example, in fig. 5 the upward succession from fine *granular* olivine to coarse *granular* olivine to coarse *hopper* olivine to *branching* olivine closely resembles the morphology and relative grain size changes previously described for harrisite (fig. 3).

TABLE I. *Compositions of Rhum harrisite crystallized*

	A	E	F		A	E	F
SiO_2	42·75	42·48	42·36	qz	—	—	—
TiO_2	0·62	0·25	1·03	or	1·12	0·47	0·95
Al_2O_3	9·01	14·78	8·70	ab	9·65	10·41	10·66
Fe_2O_3	1·51	2·05	3·16	an	18·91	34·57	17·61
FeO	11·59	8·44	9·13	ne	—	—	—
MnO	0·23	0·17	0·21	di	13·25	7·13	10·99
MgO	22·03	18·56	23·72	hy	3·68	0·86	6·03
CaO	7·21	8·79	6·41	ol	46·24	39·92	43·29
Na_2O	1·14	1·23	1·26	mt	2·19	2·97	4·58
K_2O	0·19	0·08	0·16	il	1·18	0·47	1·96
P_2O_5	0·06	0·02	0·06	ap	0·13	0·04	0·13
SO_3	0·04	0·01	0·01				
H_2O+	1·81	1·64	1·97				
H_2O-	0·40	0·34	0·45				
Total	98·59	98·84	98·63				

Si, Ti, Al, Fe (total), Mn, Mg, Ca, K, P, and S determined by XRF analysis; Na by instrumental neutron activation analysis; FeO by titrimetry; H_2O+ and H_2O- determined gravimetrically.

The preferred upward growth of *branching* olivine in comb-layered harrisite was also reproduced in these experiments (e.g., fig. 6). Examination of these crystals using the Universal Stage reveals preferred orientation with *a* elongate and close to vertical.

Thus, four distinctive petrographic features of comb-layered harrisite have been reproduced (figs. 4–6): olivine morphology, olivine morphology distribution, relative grain size distribution of olivine, and preferred upward olivine growth parallel to *a*. Identical features have been produced in runs cooling the two melts of peridotitic harrisite under the same conditions and cooling rates (Donaldson, 1975a). In all three compositions, only in the cooling rate range of 14 to 30°/hr was the layering and differentiation of olivine crystal shapes produced. At other rates only one shape of olivine grew.

In isothermal crystallization experiments on the same materials (Donaldson, 1975a, 1976) *granular* olivines crystallize at degrees of supercooling up to 20 °C, *hopper* olivines at < 10–35 °C, and *branching* olivines at 30–50 °C.

Crystallization and differentiation of charges. On cooling, the earliest nuclei of olivine form at a degree of supercooling at which the nucleation rate is large, and so growth centres are abundant. However, the growth rate is slow, so the crystals remain small. A granular olivine (0·1 mm in size) that nucleated at the top of the charge will sink to the base at approximately $2·5 \times 10^{-3}$ cm/s in 2 minutes [calculated from Stokes's Law, $\eta_{1125\,°C} = 4·2$ poise (determined using the method of Shaw (1972) and assuming 5 wt % H_2O for saturation at liquidus temperature); $\rho_{eucrite} = 2·8$ g.cm^{-3}]. These crystals form a 'cumulate', up to 1 mm thick, containing 50 to 80 vol. % olivine. With further cooling, the nucleation rate greatly decreases and the

growth rate steadily increases. Both changes promote growth of olivines larger than the original granular crystals. When the ratio of growth rate (G) to melt diffusion coefficient (D) reaches a critical value, *hopper* olivines grow (Donaldson, 1976). Further increase in degree of super-cooling promotes growth of larger *hopper* crystals. Still greater increase in degree of super-cooling further reduces both the nucleation rate and melt diffusion coefficient and probably increases the growth rate, with production of *branching* crystals at a large value of the ratio G/D (Donaldson, 1976).
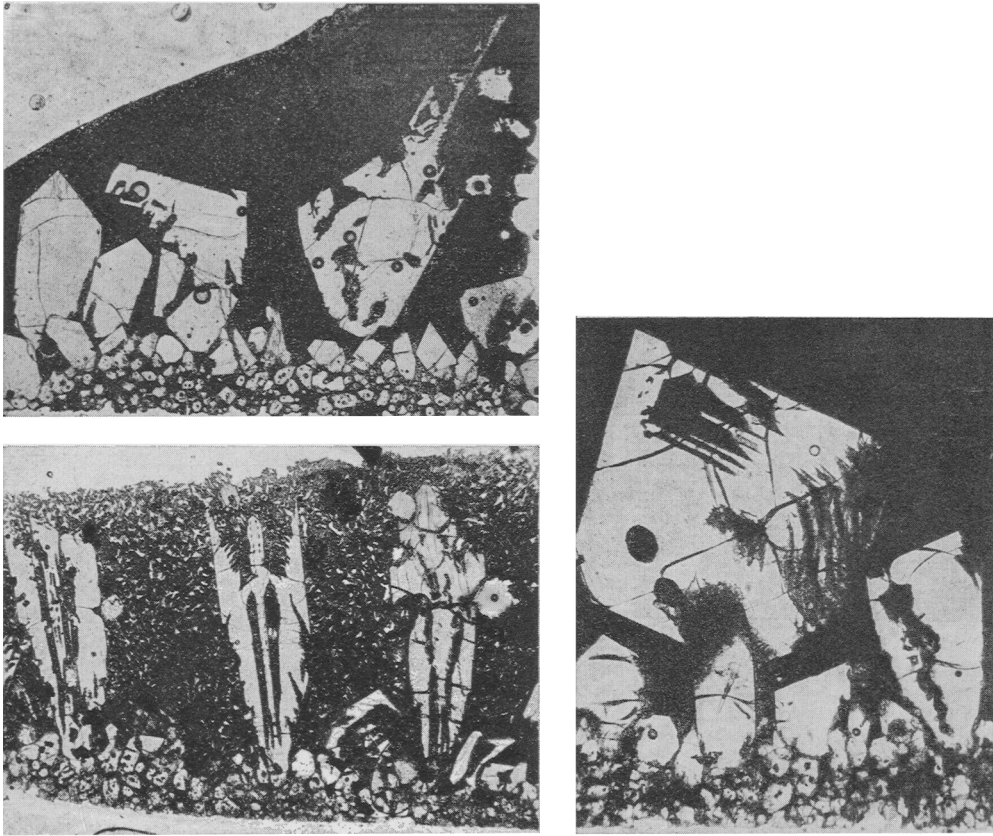
FIGS. 4 to 6: FIG. 4 (top left). Differentiation of a cooling rate run with respect to olivine grain size and shape. (Olivine eucrite with 15 wt. percent H_2O cooled at $14°$/hr. Charge is 2 mm wide). FIG. 5 (right). Upward change in olivine grain size and shape in olivine-eucrite melt with 15 wt. percent H_2O cooled at $28°$/hr. (Charge is 1·3 mm wide). FIG. 6 (bottom left). Experimental charge containing *granular* olivine overlain by large *branching* olivine. The *a* axis of all three *branching* olivines is within $20°$ of the vertical. (Olivine-eucrite with 5 wt. percent H_2O and cooled at $30°$/hr. Height of charge is 3 mm. Compare fig. 2a).

Granular olivines at the base of the charges are reverse zoned (Fo_{90-92}; determined by electron-microprobe analysis), and *hopper* olivines, 1 mm above the base, are normally zoned (Fo_{92-86}). The overlying *branching* olivines are normal-zoned along their length and across their width (Fo_{93-82}). The most magnesian portion of these elongate crystals is usually between the centre and their lowest point. *Granular* crystals are presumably reverse zoned because at the time of crystallization H_2 was still being released from the capsules due to H_2O dissociation, and Fe^{2+} in the melt continued to be oxidized to Fe^{3+}. Since later-crystallizing *hopper* olivines

are normally zoned, either loss of H_2 had ceased or (and this is more likely) the rate of Fe^{2+} depletion in the melt, due to olivine fractionation, was faster than Fe^{2+} depletion due to oxidation. These conditions also applied during formation of normal zoning in the elongate, *branching* crystals. (The olivine compositions are considerably more magnesian than those in the natural rock (Fo_{83}), because the f_{O_2} of the experiments is 10^6–10^7 orders of magnitude larger than that at the liquidus temperature of the rocks in nature.)
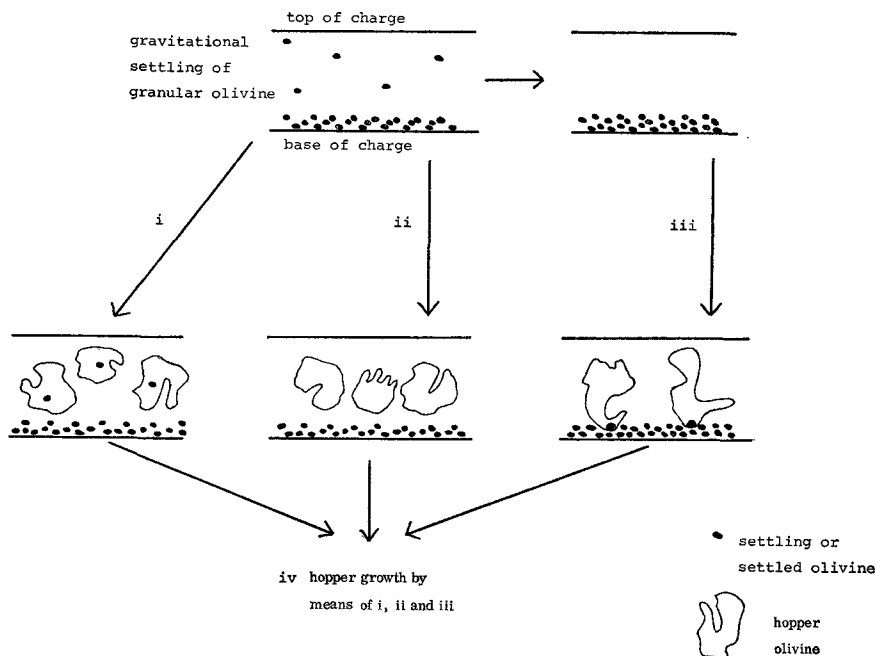

FIG. 7. Three possible origins of *hopper* olivine in differentiated crystallization runs.

Hopper olivines in the charges could grow from any of three possible nuclei (fig. 7): from settling crystals which originally were *granular* in shape, from new nuclei, or from the uppermost *granular* olivines in the mush of settled crystals. Since *granular* olivines grade into *hopper* olivines, the validity of the last suggestion is probably slight. A combination of the other two crystallization schemes is more valid.

The preferred elongation and crystallographic orientation of *branching* olivines (e.g., fig. 4), together with their zoning pattern are evidence that these crystals grew *in situ*. Otherwise, the preferred elongation direction must be attributed to settling of *branching* crystals along a preferred crystallographic direction: this is improbable. Whether the *branching* crystals grew on *hopper* olivines or from nascent nuclei (fig. 8, stages IV to Va or IV to VIb) is indeterminable. However, the zoning pattern of crystals establishes that the growth centre lay just above the mush of settled *granular* olivines.

The sorting and stratification of olivine morphologies are consistent with three possible types of nucleation history: there may be continuous nucleation throughout the charge (fig. 8); or nucleation may be continuous, but decrease in rate with time, and all nuclei, other than the initial ones, form only at the top of the charge where the olivine supersaturation is greatest; or nucleation may be discontinuous, involving crystallization and settling of *granular* olivine, followed by cessation of nucleation and then by renewed, but slower, nucleation, to provide

growth centres for *hopper* olivines. Since the form of the nucleation rate versus degree of supercooling curve for olivine in the rock melts has only one maximum (Donaldson, 1975a), the possibility of discontinuous nucleation can be rejected. However, nucleation may be *effectively* discontinuous, since a sharp decrease in nucleation rate occurs below the maximum value. Thus, after abundant nucleation of the olivines, which grow with *granular* morphology, further, but relatively slow, nucleation will continue. Whether subsequent nucleation is confined to the top of the charge cannot be determined, because olivine settles so rapidly in these

FIG. 8. Two possible origins of *branching* crystals and schematic representation of olivine nucleation and growth in cooling rate crystallization runs.

low-viscosity melts. It seems most likely that nucleation continued throughout the charge, but that at any instant the rate of nucleation and the number of nascent nuclei decreased from the top of the charge to the base. This model of crystallization is depicted in fig. 8.

In summary, olivine nucleation occurred throughout cooling, except for the period of incubation during early cooling. The rate of nucleation decreased with time, and all olivine settled towards the bottom of the capsule. If nucleation first occurred at the degree of supercooling at which nucleation rate is close to maximum, granular olivine crystallized, this being an attempt by the system to relieve supersaturation by abundant nucleation. With further cooling, the nucleation rate rapidly diminished. In order to continue relief of supersaturation, the growth rate increased and larger, *hopper* olivines grew. With further increase in degree of supercooling, the nucleation rate tended to zero, and with the growth rate being high, *any* available olivine crystal grew readily. Those crystals with the *a* axis approximately perpendicular to the layering grew most rapidly as *branching* crystals, thereby producing a comb layer resembling comb-layered harrisite.

Petrographic examination of comb layers in several lavas and intrusions (Lofgren and Donaldson, 1975) suggests that a similar crystallization history, in which the nucleation rate and the number of crystals (of the phase forming branching crystals) suspended in the magma both decrease essentially to zero, occurs during formation of all natural comb-layered rocks.

This discussion has ignored the fact that with progressive fractionation of *granular* olivine in the cooling rate experiments, the degree of olivine supersaturation of the melt might diminish so that *polyhedral* olivine crystallized. However, by comparison with isothermal runs (Donaldson, 1976), crystallization of *hopper* olivine, and then *branching* olivine, after *granular* olivine, indicates that the supersaturation continued to increase (cf. Kirkpatrick 1975).

Relevance to the origin of comb-layered harrisite and to comb-layered rocks in general

Crystallization of comb-layered harrisite. An analogue of comb-layered harrisite has been made by cooling three hydrous ultrabasic melts at *constant* rates of 14, 28, and 30°/hr. Thus, continuous, rather than abrupt, changes are likely in the temperature, pressure, and other intensive parameters of the natural harrisite-forming magma. An origin for harrisite involving emplacement of new magma to explain the change from cumulate to harrisite can therefore be rejected. Harrisite and associated cumulate are two textural extremes of ultrabasic rock related by differences in olivine growth parameters that result from differences in degree of magma supercooling and supersaturation. Olivines in harrisite crystallized at a larger degree of supercooling than those in cumulate. By comparison of the experiments with harrisite, it is clear that the upward transition from cumulate to harrisite results from continuous increase in olivine supersaturation and an increase in supercooling (but see penultimate section). Olivine crystals always grew under water-saturated conditions in the differentiated runs, indicating that formation of harrisite is not the result of a change from water-undersaturated to water-saturated conditions (or vice versa).

Layering is not produced when the olivine-eucrite melt is cooled at 1 atm. under anhydrous conditions (Donaldson, 1976). This is due to the higher viscosity (by a factor of 10) of the anhydrous melt relative to the water-saturated melt and hence to less rapid settling of olivine. Although this fact does not imply that the parent magma of harrisite was either water-saturated or of low viscosity, it suggests that low viscosity would aid comb layer formation (cf. Moore and Lockwood, 1973), by promoting rapid removal, by settling, of crystals growing in the magma.

Synthesis of certain textural features of harrisite does not imply that the cooling rate found to produce in the laboratory a texture similar to that of the natural rock also caused its crystallization in nature. Differences in crystal size, volume of melt, crystal settling distance, and degree of melt fractionation between the experimental system and the natural one are such that the cooling rate during natural harrisite crystallization will be less than that in the experiments. How much less is unknown because the scaling factors relating the experiments to natural crystallization are unknown; it must, however, be a rate compatible with the settling rates of *granular* and *hopper* olivines. The experiments indicate that the rate has a restricted range of values. In contrast, the degrees of supercooling for crystallization of particular growth shapes, deduced from isothermal experiments (Donaldson, 1975a, 1976), are probably representative of those for harrisite.

Differences in olivine content between melts have little effect on the degree of supercooling at which each olivine morphology crystallizes; they do affect the cooling rate (Donaldson, 1975a, 1976). The effect is such that if the parent magma of harrisite were basalt rather than olivine-eucrite, faster cooling rates than those determined in the laboratory would cause harrisite to crystallize.

Cause of vectorial crystallization in comb-layered rocks. Wadsworth (1961, pp. 60–1) ascribed the preferred elongation direction and crystallographic orientation of branching olivines in comb-layered harrisite to competitive growth, suggesting that settled, cumulus crystals, oriented with (010) vertical, grew upwards faster than crystals of other orientations. By 'budding' these crystals expanded laterally into a giant linked parallel-growth structure (Donaldson, 1974, 1976), thereby obstructing growth of adjacent crystals. In view of the lack of obstruction of growth between adjacent oriented olivines in experiments simulating comb-layered harrisite (e.g., fig. 4), in many harrisite comb-layers (e.g., fig. 5a; Drever and Johnston, 1972), and also in other examples of comb-layering, another explanation of preferred elongation of crystals in comb-layered rocks is needed.

Preferred crystallographic elongation direction of crystals is consistently associated with directional crystallization of a solidification front (Knight, 1967), with the crystal elongation aligned parallel to the vector of unidirectional solidification.

Unidirectional solidification results from directed heat flow along a thermal gradient or directed solute flow along a compositional gradient. To prevent disturbing these flow regimes, motion of the magma must be negligible [contrast Platten and Waterson (1969) and Moore and Lockwood (1973)].

Withdrawal of heat from a magma through a boundary causes a thermal gradient to form perpendicular to the boundary. Elongate crystals can grow along the gradient from low temperature to high in constrained fashion (Lofgren and Donaldson, 1975). This is the cause of formation of the 'columnar zone' of crystals, with preferred elongation, in ingots of rapidly cooled metals (e.g. Walton and Chalmers, 1959). However, elongate olivines did not grow along an externally-applied thermal gradient in the cooling experiments reproducing comb-layered harrisite. Neither could there have been a thermal gradient within charges, because heat removal from the charges is isotropic. Rather the elongate crystals probably grew along a concentration gradient in the melt, the gradient being established by ionic exchange between the 'intercumulus' melt and the overlying melt.

The most likely location for directed solute flow in a magma chamber, resulting in *initiation* of oriented growth, is in magma just beyond a solidifying crystal mush at the floor or margins of the chamber. Here, flow of components exists, as ions within the mush exchange with those from the supernatant magma (Hess, 1939; Wager *et al.*, 1960). Because the elongate crystals in comb layers grow in constrained fashion, the concentration gradient in the magma adjacent to each crystal will *maintain* directed flow of components towards the crystal (Lofgren and Donaldson, 1975).

Non-equant shape and the formation of faces on crystals testify to the vectorial anisotropy of crystal growth rate (Eitel, 1965), probably as a result of anisotropic thermal conductivity of crystals (cf. electrical conductivity; e.g. Duba, 1972). During comb layer formation the growth anisotropy is greatly enhanced when a particular crystallographic direction lies closely parallel to the direction of heat or solute flow. It is therefore likely that in comb layers all orientations of nucleus are available for elongate branching growth, but only nuclei of specific orientation grow to any significant size. These few crystals grow along one crystallographic direction so rapidly that other nuclei have no opportunity for growth, i.e., growth components are removed from the melt before the unfavourably oriented nuclei grow to an appreciable size. Thus, the cause of the vectorial crystallization in comb-layered rocks is 'competitive growth', in the sense that the crystals compete for available solute on the basis of their orientation with respect to the crystallization front, but not in the sense of mutual obstruction.

Initiation, termination, and location of comb layer formation. In comb-layered rocks there is never evidence for growth of the parallel, branching, elongate crystals *within* the magma cham-

ber (i.e. unconstrained growth); instead they always crystallized on or within a few millimetres of the walls and margins of magma bodies, or on cognate xenoliths (resulting in 'orbicular' rocks, e.g. Mutanen, 1974; Van Diver and Magetti, 1973; Bryhni and Dons, 1975). These relations indicate that a solid object on, or very close to which crystals grow is essential for formation of branching crystals and also that a thermal gradient probably exists in the magma (Lofgren and Donaldson, 1975). [In metal casting, elongate crystals of preferred orientation also commence growth on, or very close to, the cast wall (Chalmers, 1963, p. 260).] The value of the cooling rate at the crystallization location is critical to maintenance of conditions for comb layer formation. If it increases, magma ahead of the advancing comb layer will supercool sufficiently to cause homogeneous nucleation in the bulk of the magma. By removing material from the magma needed by the elongate crystals for growth, these new crystals will terminate elongate crystal growth in the comb layer. On the other hand, if the cooling rate decreases, the elongate crystals reach into magma that is too little supercooled to permit continued elongate branching growth. Thus, the rate of advance of the isotherms into the magma should be comparable to the crystal growth rate. If this steady state condition persisted during crystallization of a body of magma, at a suitable cooling rate, the whole body would crystallize as a comb-layered rock. (It is possible that the upward textural change from comb-layered harrisite to cumulate (fig. 2) results from the isotherms advancing more rapidly than the elongate crystals.)

In summary, certain criteria have to be fulfilled to cause formation of comb layers in a magma:

The magma adjacent to the comb layer should be stagnant.

There must be a suitable substrate for growth within the magma body (xenolith), or at the margin of the body.

Suspended crystals of the phase growing in an elongate manner in the comb layer should be absent or in low concentration in the magma.

The degree of supercooling of the magma should have a value at which the rate of homogeneous nucleation is low. It should also be of the appropriate value to promote branching crystal growth, i.e., the ratio of growth rate to diffusion coefficient should be within a certain range (Donaldson, 1974).

A thermal gradient probably exists at the margins of magma chambers forming comb layers, but the experiments indicate that this is not an essential condition for comb layer formation.

A possible isothermal origin of comb layering

So far, this paper has followed previous workers on comb layering in suggesting that the transition from 'normal' rock to comb-layered rock is the result of a change in degree of magma supercooling. This section describes how the transition could occur at *constant* temperature and still be consistent with the experimental results.

Typical curves for the variation of crystal growth rate (G) and nucleation rate (N) with degree of supercooling are shown in fig. 9, where N is for the condition of *spontaneous* nucleation. If the value of N increased at an isotherm (e.g. due to addition of crystals to the melt), there would be a reduction in G, due to competition for diffusing solute (Doremus, 1973, p. 65). The reverse of this behaviour suggests an origin for comb layer formation. If slightly supercooled magma becomes sufficiently cleared of crystals, the remaining crystals in suspension have to compete less for solute, supersaturation locally increases, and therefore crystals

grow faster. This situation arises if the number of crystals removed from the melt per unit time (N^1 in fig. 9) exceeds N. The increase in G could be sufficient to promote branching crystal growth and comb layer formation. This mechanism does *not* require change in the degree of supercooling to enhance supersaturation of the magma, only a decrease in abundance of suspended crystals (cf. harrisite) and a compositional or thermal gradient (or both) in the magma. Operation of such an isothermal mechanism in the Rhum intrusion could remove the need to explain the apparent substantial increase in degree of supercooling to at least 30 °C, in passing from cumulate into comb-layered harrisite.
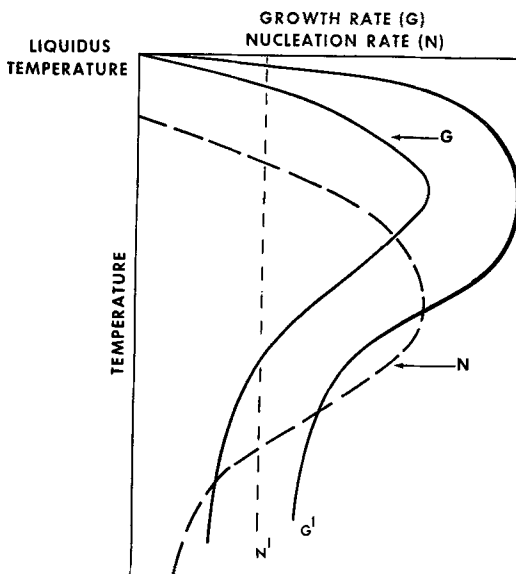
FIG. 9. Forms of the growth rate and nucleation rate versus supercooling curves for a phase crystallizing from a melt of its own composition under conditions of spontaneous crystallization. N^1 is the number of crystals settling (in same units as N) and G^1 is the effective growth rate resulting from decrease in number of available growth centres due to crystal settling.

No information is available on how large an increase in G might result from removal of crystals. Absence of comb layer formation in the isothermal crystallization experiments (Donaldson, 1976) suggests that this mechanism may be insufficient to cause comb layer formation without increase in degree of supercooling. However, it should be noted that in these isothermal experiments the melt is fractionating rapidly during crystallization, thereby continuously reducing the degree of supercooling of the melt. In a natural magma the extent of fractionation would be less.

Even if increase in degree of supercooling is essential to the initiation of comb layer formation, it is important to recognize that there is a decrease in abundance of crystals as rock free of skeletal crystals gives way to comb-layered rock (e.g. fig. 3) and hence removal of crystals from magma must be a contributory factor in increasing G and promoting comb layer formation. Furthermore, J. Kirkpatrick (pers. comm., 1975) points out that decrease in nucleation rate would cause increase in degree of supercooling in order to satisfy heat flow requirements. These comments suggest that it is unlikely that there is a unique set of conditions causing crystallization of comb layers in all comb-layered bodies.

Summary and concluding comments

The characteristic distribution of olivine grain sizes and shapes present in comb-layered rocks of one locality have been reproduced under a restricted range of cooling rates (14 to 30°/hr). These rates represent a maximum value for formation of the comb layering in nature. The elongate combed olivines in harrisite *apparently* grew as the magma locally supercooled to at least 30 °C. It is suggested that the branching crystals in most comb layers, including comb-layered harrisite, probably grew along thermal gradients. However, the experiments indicate that a thermal gradient in magma close to the object (chamber wall or xenolith) on which the elongate branching crystals grow is not the only possible cause of comb layer formation; a compositional gradient would be equally effective. By means of a compositional gradient combined with a decrease in availability of nuclei, it is *in principle* possible to form comb layers under isothermal conditions. Once formation of comb layering has begun, the isotherms in the magma must advance at the same rate as the crystallization front, otherwise comb layer formation ceases.

This study highlights current ignorance of the crystallization of large bodies of magma in respect of nucleation, growth rate, and controls of the supersaturation of phases. Each of these parameters is critical in development of the various textural types of cumulate distinguished by Wager *et al.* (1960) and in determining the liquid line of descent of a magma and the composition of its differentiates. The following aspects are of particular importance: what are the magnitudes of the changes in growth rate, nucleation rate, and supersaturation of a phase as the concentration of crystals in suspension in a magma decreases due to crystal settling and accumulation? How does preferential settling of olivine from a magma affect the crystallization (nucleation, growth rate, growth mechanism, and composition) of more slowly settling pyroxene and plagioclase crystals? How does the proportion of each phase in a suspension of crystals affect crystallization of other phases? How rapidly, and over what distance can diffusion between intercumulus melt and supernatant magma take place to prevent zoning of cumulus crystals? How do nucleation and growth take place in a thermal gradient and in a compositional gradient at the margin of a magma body, and do these gradients enhance anisotropic growth rate of crystals?

Further non-equilibrium crystallization experiments in which crystal settling and its effect can be studied are needed to understand these kinetic aspects of the crystallization of magmas and to explain certain petrographic features of rocks.

REFERENCES

Bryhni (I.) and Dons (J. A.), 1975. *Lithos*, **8**, 113.
Chalmers (B.), 1963. *Principles of Solidification* (New York).
Donaldson (C. H.), 1974. *Geol. Soc. Am. Bull.* **85**, 1721.
——— 1975a. *A Petrogenetic Study of Harrisite in the Isle of Rhum Pluton, Scotland.* (Unpubl. Ph.D. thesis, Univ. St. Andrews).
——— 1975b. *J. Geol.* **83**, 33.
——— 1976. *Contrib. Mineral. Petrol.* **57**, 187.
Doremus (R. M.), 1973. *Glass Science* (New York).
Drever (H. I.) and Johnston (R. J.), 1972. *Meteoritics*, **7**, 327.
Duba (A.), 1972. *J. Geophys. Res.* **77**, 2483.

Eitel (W.), 1965. *Silicate Science vol. III. Dry Silicate Systems* (Academic Press).
Harker (A.), 1908. *The Geology of the Small Isles of Inverness-shire.* (Mem. Geol. Surv., Scotland.)
Hess (H. H.), 1939. *Trans. Am. Geophys. Union*, 3, 430.
Jackson (E. D.), 1971. *Fortschr. Mineral.* 48, 128.
Kirkpatrick (R. J.), 1975. *Am. Mineral.* 60, 798.
Knight (C. A.), 1967. *The Freezing of Supercooled Liquids* (van Nostrand).
Lofgren (G. E.) and Donaldson (C. H.), 1975. *Contrib. Mineral. Petrol.* 49, 309.
Moore (J. G.) and Lockwood (J. F.), 1973. *Geol. Soc. Am. Bull.* 84, 1.
Mutanen (T.), 1974. *Bull. Geol. Soc. Finland*, 46, 53.
Platten (I. M.) and Watterson (J. S.), 1969. *Nature*, 223, 286.
Shaw (H. R.), 1972. *Am. J. Sci.* 272, 870.
Taubeneck (W. H.) and Poldervaart (A.), 1960. *Geol. Soc. Am. Bull.* 71, 1395.
Van Diver (B. B.) and Magetti (M.), 1973. *Geol. Soc. Am. Annual Meet. Abstr.* 7, 846.
Wadsworth (W. J.), 1961. *Philos. Trans. R. Soc.* B244, 21.
Wager (L. R.), 1968. In *Basalts* (eds. H. H. Hess and A. Poldervaart) (Interscience, N.Y.)
—— and Brown (G. M.), 1951. *Geol. Mag.* 88, 166.
—— —— 1968. *Layered Igneous Rocks* (Oliver and Boyd).
—— —— and Wadsworth (W. J.), 1960. *J. Petrol.* 1, 73.
Walton (D.) and Chalmers (B.), 1959. *Trans. Metall. Soc. AIME*, 215, 447.