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The origin of rhythmic layering

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SUMMARY. Rhythmic layering in the Skaergaard intrusion shows variation in crystal size and in modal proportions of primocrysts with structural height. These changes are ascribed to variations in nucleation rates of primocrysts. The nucleation theory requires that crystallization occurs under supercooled conditions, and that the crystallization of one primocryst phase may change the composition of the magma in such a manner that the nucleation rates of other primocrysts are influenced. Both these constraints appear to have been fulfilled for the Skaergaard intrusion.

THE fractionation processes occurring in deep-seated magma chambers cannot be observed directly but the cumulates of layered intrusions afford a continuous record of the crystallization processes in magma chambers, and thus allow detailed evaluation of the fractionation conditions. That mineralogical variations agree with experimentally determined phase relations indicates that the crystallization of magmas at least approximates to thermodynamic equilibrium conditions. The rhythmic layering of layered intrusions is explained by the equilibrium condition, and suggests that other processes are involved.

The present investigation of rhythmic layering in the Skaergaard and Rhum intrusions suggest that the rhythmic layering is caused by rhythmic nucleation events in a slightly supersaturated magma, a theory originally proposed by Zyl (1959). Within small degrees of supersaturation, the crystallization of magma will still be governed by phase relations, as the kinetics of crystallization will be related to the phase relations, and it is unlikely that the crystallization deviates more than marginally from an equilibrium one.

The layering from two drill cores from the Skaergaard intrusion of the 1966 expedition led by W. A. Deer was investigated, and unit 14 from the Rhum intrusion was studied in the field.

Lower and hidden zone of the Skaergaard intrusion

The drill core 1 of the 1966 expedition from the NW part of the intrusion is 349 m long and penetrated about 150 m below the lowest exposed part of the layered series. Variations in modes and anorthite content of plagioclase was reported by Maaløe (1976), and the variation in composition of pyroxenes and olivine was reported by Niwe (1976). The position of major rhythmic layering and the onset of laminar convection is shown in fig. 1. The rhythmic layering is due to variations in the concentrations of olivine and plagioclase primocrysts. The thickness of the individual layers varies widely from several centimetres to some metres. There is no systematic variation in the thickness of the rhythmic units with structural height. The gravity-stratified layered is the predominant type, but some diffuse bands consisting of olivine alone or both olivine and plagioclase primocrysts and a few coarse grained layers are present as well. The first primocryst-like olivine appears at −140 m, and the first layer of olivine appears at −113 m (fig. 1) in which positions are measured negatively from the surface.

The gabbro of the lowermost part of the drill core below −130 m has doleritic texture and displays no evidence of lamination. Lamination begins gradually at this level and is well developed at −120 m. In the laminated gabbro, olivine may be wrapped around by tabular plagioclase crystals in the manner shown in fig. 1. These plagioclase crystals are symmetrically situated with respect to the plane of lamination of the cumulate suggesting that the plagioclases were pressed from either side towards the olivine. The lamination may therefore have originated by compaction of the cumulate, caused by the load of successive cumulate, as was considered by Wager and Brown (1967). The lamination has been related to convection currents, and the lineation observed in the Rhum intrusion (Brothers, 1964) clearly demonstrates that lamination may be related to convection currents. However, the present evidence would suggest that lamination is not necessarily due to convection currents, occurring below the inferred onset of convection. The relationship between the effect of load and lamination might appear in contradiction with the lowermost part of the drill core displaying

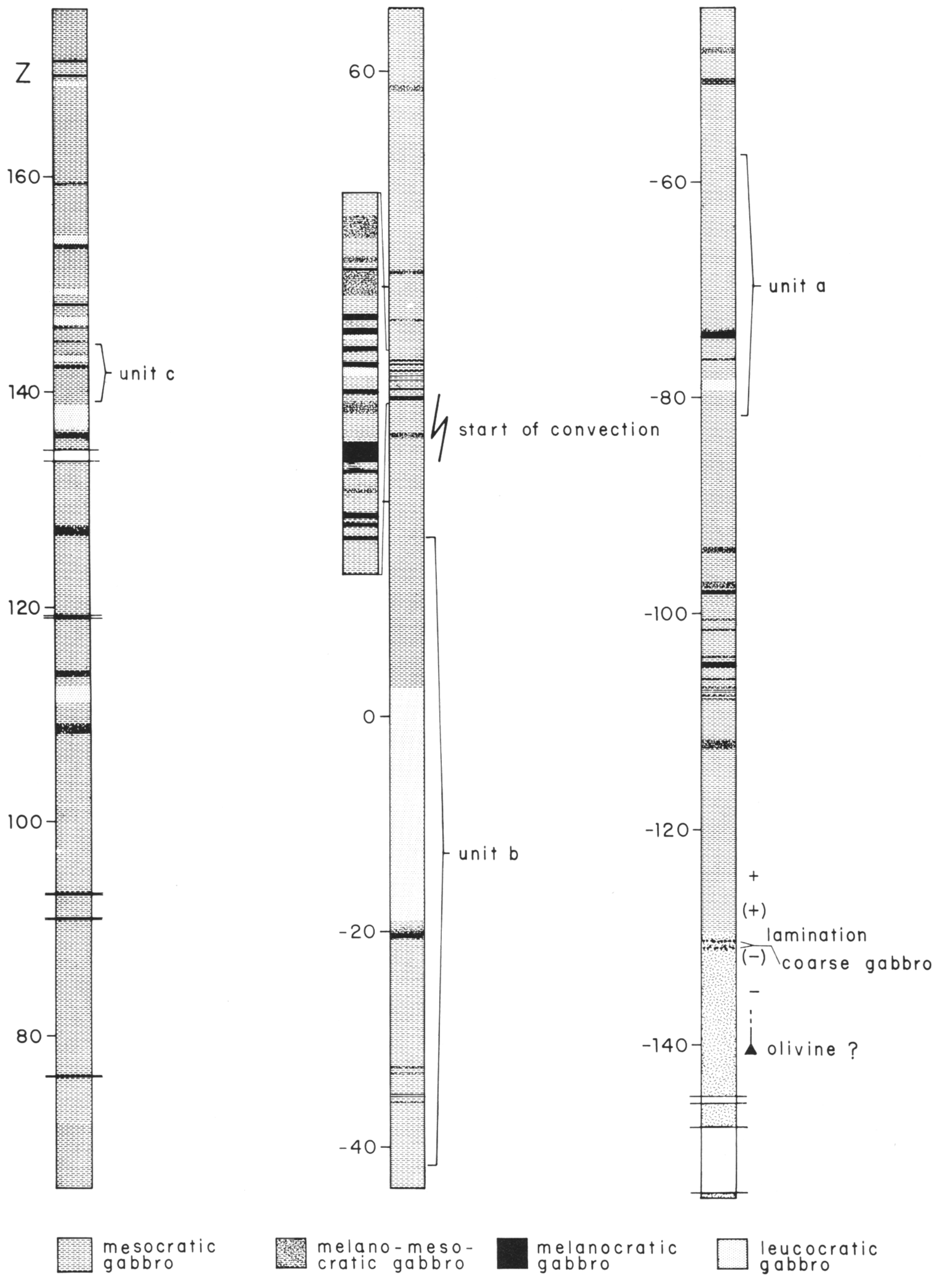

FIG. 1. Petrographic features of drill core 1. The structural height and the level of start of convection were estimated from the variation in An% of plagioclase (Maaløe, 1976). The more dominant rhythmic layering is shown. Horizontal lines show the position of dykes cutting the drill core. The gabbro of the lower part of the drill core contains several olivine bands, while the first leucocratic layer is situated at −79 m.

doleritic texture. However, the anorthite content of plagioclase from the gabbro at −145 m is identical to that of the perpendicular feldspar rock (Maaløe, 1976), which formed after only 3 m of chilled margin was consolidated. The gabbro of the lowermost part of the drill core apparently formed only metres from the very contact of the intrusion. This part of the cumulate series therefore consolidated before the load of subsequent cumulate allowed reorientation of the plagioclase primocrysts. The plagioclase composition and the texture of the gabbro near to and below −145 m were probably therefore formed only metres from the bottom of the intrusion. Drill core 1 consequently contains the very first formed rhythmic layers of the Skaergaard intrusion. As long as only plagioclase formed primocrysts there was no formation of rhythmic layering, but soon after olivine began to form primocrysts the formation of rhythmic layering was initiated. It may be noted that rhythmic layering also is present below the level of onset of convection (fig. 1).

Rhythmic layering of the Skaergaard intrusion

Four banded or rhythmic units of the Skaergaard intrusion have been investigated in some detail (Maaløe, 1974), units *a* and *c* of core 1 and the layering of core 2 from the Triple Group of the Middle Zone are considered. Mineral proportions were obtained by point counting 700–1100 points per slide. The number of crystals in the gabbro was estimated from the crystal index, which is defined as the number of crystals of a given mineral in 1 cm^3 of that mineral. The crystal index differs from a similar term, the crystallinity, defined by Wager (1961). The crystallinity of a mineral depends on the mode of the mineral, while the crystal index only depends on the average size of the mineral. If the total number of crystals of a mineral in a thin section is N, and if A is the area of the thin section, the number of crystals per cm^2 is N/A. Assuming the crystals are equidimensional and evenly distributed in the rock, the number per cm^3 of rock is given by $C = (N/A)^{3/2}$. The calculation method of the crystallinity was not mentioned by Wager (1961), but his figures suggest that C, as calculated here, is the crystallinity. If the mode percentage of a mineral is M, the crystal index is given by: $n = (N/A)^{3/2}/(0{\cdot}01M)$. A fine-grained mineral has a large crystal index, while a coarse-grained one has a small crystal index. The extreme variation in the crystal index for the Skaergaard intrusion is from 20 to 63 000, whereas the normal range is from 100 to 3000. The observed variation in crystal index is based on counts from 800 to 3000 crystals per thin section (Maaløe, 1974).

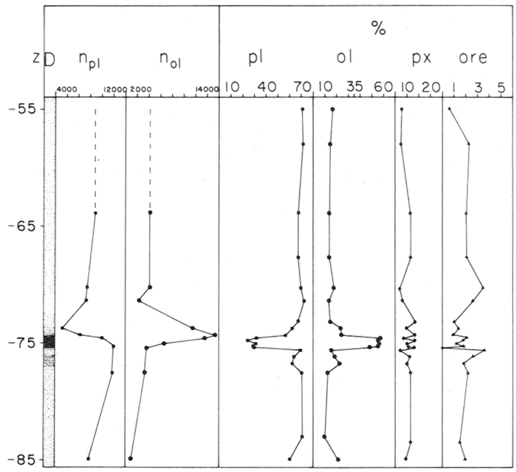

FIG. 2. Rhythmic layering of unit a of the hidden zone. The appearance of the layering is shown in column D. Abbreviations: n_{pl}: crystal index for plagioclase, n_{ol}: crystal index for olivine. The modal contents of plagioclase (pl), olivine (ol), augite and pigeonite (cpx), and ore are shown.

Unit a. The gabbro just below the melanocratic band of unit a is homogeneous and displays only faint layering (fig. 2). The melanocratic band is due to a concentration of olivine primocrysts. The mesocratic gabbro contains 18 % olivine, while the melanocratic band contains 60 % olivine. The mode of olivine changes abruptly both at the bottom and top of the band, but is rather constant within the band. The variation in crystal index differs from this pattern. The index increases abruptly at the bottom of the band, continues increasing throughout the band, and reaches a maximum at the top. The diameter of olivine varies from 0·05 mm to 1·0 mm, the size range being the same for both meso- and melanocratic gabbro, while the size distribution varies.

Unit c. This unit is a small rhythmic layer. The transition from mesocratic to melanocratic gabbro occurs within 2 cm, with a simultaneous increase in the crystal index (fig. 3). The olivine content of mesocratic gabbro below the layer is 10 %, it increases to 30 % slightly above the base of the layer, whereafter it increases further to 50 %. At the topmost part of the layer the olivine content decreases abruptly from 50 % to 18 % within 0·5 cm. The plagioclase content of the leucocratic part of the layer increases suddenly from 40 to 75 %, whereafter it drops to the mesocratic value of 55 %.

The crystal index of plagioclase displays an ill-defined maximum in the leucocratic layer. The size range of olivine in the melanocratic layer is from 0·05 to 3·0 mm, whereas the size range in the

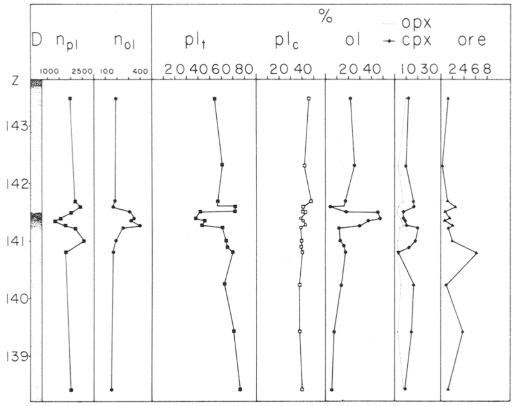

FIG. 3. Rhythmic layering of unit c of LZa. Abbreviations as in fig. 2, except that pl_c shows the proportion of primocryst cores of plagioclase crystals. The cores are rather constant and independent of the layering. The total modal variation for plagioclase (pl_t) is therefore related to a variation in the accumulation of primocrysts. Orthopyroxene (opx) was formed by inversion of pigeonite.

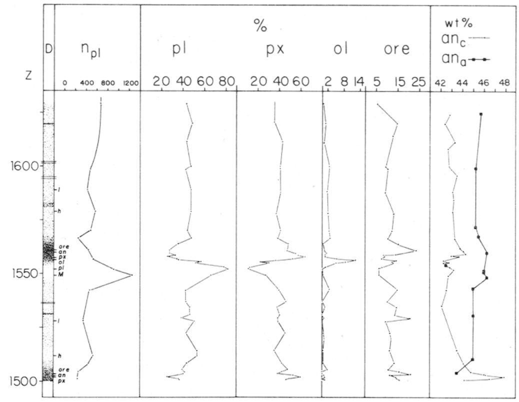

FIG. 4. Rhythmic layering of the triple group from the upper part of MZ. The crystal index for plagioclase attains its maximum value (M) in the leucocratic layer, but below the maximum in the mode (pl). Olivine forms primocrysts in the melanocratic layer (ol), but is only present as reaction rims in the mesocratic gabbro. Abbreviations: pl_t, total mode of plagioclase; pl_c, the percentage of the core part of plagioclase crystals in relation to the total mode of plagioclase; px_t, total amount of pyroxenes; ol, mode of olivine; an_c, An% of cores estimated by universal stage and maximal extinction; and an_a, the average An% of plagioclase estimated by X-ray fluorescence (Maaløe, 1974).

mesocratic gabbro is from 0·05 to 1·5 mm. The maximum for the crystal index of olivine is not at the top of the layer but near the bottom. Augite did not form primocrysts at this level of the layered series; the modal minimum displayed by this mineral in the melanocratic layer might suggest that the layer was formed by relatively fast accumulation.

The triple group is situated in the upper part of the Middle Zone and consists of three conspicuous rhythmic layers (Wager and Brown, 1967). In the layered series 200 m below, there is a series of rhythmic layers with a thickness of about 1 m. In the layered series above the triple group the gabbro is without well developed rhythmic layering. Core 2 penetrated 80 m of the gabbro above the triple group and its two uppermost layers (fig. 4). There is 20 m between the two lower layers of the triple group and 60 m between the two upper ones.

The plagioclase mode increases gradually below the third layer from the mesocratic value of 45–50% to 85%, and decreases again gradually to 20–25% in the melanocratic gabbro. The relative proportions of plagioclase cores to margins varies little despite the variation in mode. The plagioclase crystal index displays more regular variation than the modes. It begins to increase at the base of the leucocratic layer and reaches a maximum (at *M*, fig. 4) slightly above the maximal mode. The index decreases thereafter throughout both the leucocratic and melanocratic layers, and reaches a minimum slightly above the melanocratic layer. The gabbro is mesocratic above the rhythmic layer and the crystal index of plagioclase has a minor maximum and minimum at h and l respectively. The modes of pyroxene and ore increases in the melanocratic layer, but the maximum values are obtained at different structural heights (fig. 4). Olivine occurs as coronas around opaque minerals in the mesocratic gabbro, and does not form primocrysts at all, except for possible rare crystals. Nevertheless, olivine occurs as a cumulate mineral in the melanocratic layer and must have formed primocrysts during a short period of crystallization. The formation of olivine primocrysts is evident from textural features, and the greatest contents of olivine and ore occur at different levels, suggesting that olivine was not formed by reaction of ore. The An% is larger in the leucocratic and melanocratic layers than in the mesocratic gabbro, but the An% of the cores, that is the primocrysts of plagioclase, do not display any marked systematic variation. The margins of the reversely zoned plagioclase developed with a higher An%.

The layering of the triple group is different from that of the typical layering of the Skaergaard intrusion. Not only are the layers relatively thick, but the sequence of melanocratic and leucocratic layers differ. The normal sequence is mesocratic–melanocratic–leucocratic–mesocratic. The sequence of the triple group is the opposite, being mesocratic–leucocratic–melanocratic–mesocratic.

Unit 14 of the Rhum intrusion

The Rhum layered series consists of a regular series of at least fifteen rhythmic units which are from about 50 to 100 m thick, and consist of an olivine cumulate followed by an olivine + plagioclase cumulate (allivalite; Harker, 1908). Some of the units are separated by a millimetre-thick layer of chromite (Brown, 1956). In the olivine cumulate, plagioclase forms poikilitic crystals enclosing olivine and chromite, and olivine and chromite are the only primocryst phases of the olivine cumulate. In the allivalite, both olivine and plagioclase forms separate crystals, and Brown (1956) suggests that both minerals formed primocrysts. The origin of olivine as primocrysts in the allivalite is very likely as the allivalite contains several fine-scale layered bands with a high olivine content (fig. 5). The typical fine-scale layering of the allivalite consists of alternating bands of allivalite and olivine cumulate, both being centimetres thick.

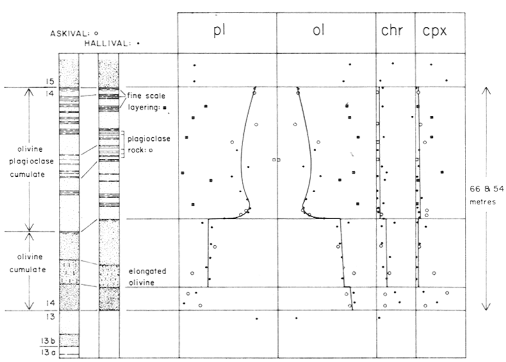

FIG. 5. Rhythmic layering of unit 14 from the Rhum intrusion. The diagram is considered preliminary as the modes of allivalite show some scatter. The appearance of the layering in the field is shown for profiles at Askival and Hallival in the two left columns. Unit 14 was estimated as being 66 m and 54 m thick at Askival and Hallival, respectively, but is shown here with the same thickness for convenience of comparison. The variation in modes of plagioclase (pl), olivine (ol), chromite (chr), and augite (cpx) was estimated from thirty-six thin sections, total counts being from 900 to 1500.

On Hallival, some bands consist of nearly pure plagioclase, but similar bands were not observed on Askival. The transition from allivalite to olivine cumulate is gradual: allivalite starts to contain fine-scale bands of olivine cumulate increasing in thickness until allivalite disappears (fig. 5).

The modes of unit 14 are shown in fig. 5. In the field allivalite looks homogeneous, but the modes show that this rock displays variation in composition, although the variation shown in fig. 5 is tentative. The lower part of the olivine cumulate contains only slightly more olivine than the upper part. The plagioclase first increases rapidly near the base of the allivalite and reaches a maximum. Later it increases again towards the top of the allivalite layer (fig. 5). The fine-scale layers of allivalite have a high content of olivine and sometimes of plagioclase.

Olivine and chromite formed primocrysts during the initial formation of unit 14. During the final formation of the olivine cumulate, plagioclase began to form primocrysts together with olivine. The initial crystallization of plagioclase occurred in short pulses as is evident from the fine-scale layering near the top of the olivine cumulate. During the accumulation of the allivalite, plagioclase may have ceased to form primocrysts as is evident from the fine-scale layering. Chromite is present in both types of layers, and may have formed primocrysts throughout the formation of the layered units. The presence of tiny chromite bands at the transition from allivalite to olivine cumulate may indicate a pause in the crystallization of olivine and plagioclase and time may have elapsed between the allivalite ceasing to accumulate and olivine starting.

The layering described above shows different features, and cannot have originated in exactly the same manner. The following features of the layering are considered noteworthy: (1) The Skaergaard gabbro may have bands of pure olivine that are not associated with a plagioclase layer. These bands cannot have originated by intermittent currents, the magma forming the bands must have had a higher olivine content than the magma forming the mesocratic gabbro. The same applies to the rhythmic units in the Rhum intrusion where the olivine cumulate is not associated with a compensating leucocratic layer. (2) A mineral not occurring as primocryst in the mesocratic gabbro may form primocrysts in a rhythmic unit. (3) The crystal index in rhythmic layers can differ from that in mesocratic gabbro; in general the crystal index for a mineral is high in a layer where it has a high concentration. (4) The transitions between layers may be abrupt or gradational.

Theories for the origin of rhythmic layering

The origin of rhythmic layering might be multiple intrusion (Brown, 1956; Irvine, 1974), intermittent currents (Hess, 1960; Wager and Brown, 1967) or rhythmic nucleation events in the magma (Zyl, 1959; Wager, 1961; Hawkes, 1967; Maaløe, 1974; Goode, 1976). It is not likely that each intrusion has its own mechanism as very similar rhythmic layering is observed in different intrusions, and the same intrusion may display different types of layering.

Multiple intrusion might be excluded as an origin of the rhythmic layering in the Skaergaard intrusion, as there is no evidence of disturbance of the layered series. Considering that there are hundreds of rhythmic layers in the layered series an intensive intrusive activity must have occurred if the rhythmic layers formed by multiple intrusion, but there is no evidence for such activity.

The intermittent current theory suggests the intermittent flow of magma from the roof region of the magma chamber towards the bottom (Wager and Brown, 1967). The primocrysts in these flows accumulate on the bottom, and as olivine and augite have a higher density than plagioclase, a femic bottom layer is formed below a leucocratic layer of plagioclase. The variation in the crystal index clearly excludes rhythmic layering originating by intermittent current activity. The crystal index should display an abrupt decrease on the transition from a mesocratic to a melanocratic layer, which is the opposite of what is observed. The thorough investigation by Pulvertaft (1965) of a layered dyke of basaltic composition from the Gardar province, East Greenland, affords substantial evidence that no current activity can be related to the formation of rhythmic layering in the dyke. Also there is no evidence for multiple intrusion forming rhythmic layering in the dyke.

The origin of rhythmic layering is considered to be related to rhythmic nucleation in the magma caused by slightly supersaturated crystallization conditions. Before the nucleation theory is considered in more detail its preconditions will be evaluated.

Preconditions for the nucleation theory. The nucleation theory assumes that the nucleation and crystallization of different minerals might interfere so that the nucleation rate for one mineral is influenced by the crystallization of other minerals. The theory therefore requires that the crystallization of olivine results in a greater potential for plagioclase to nucleate. This interference is only possible if the composition of the magma between the suspended olivine primocrysts is depleted in the olivine-forming component. As diffusion rates in silicate melts are small, this condition results in slow nucleation and growth rates, and restricts the cooling rate of an intrusion and the average distance between primocrysts in the magma. The average distance between primocrysts in the Skaergaard magma will be considered here.

The average distance between primocrysts may be estimated approximately from the average cooling rate of the intrusion. The total crystallization time for the liquidus phases of the Skaergaard intrusion has been calculated as 12 750 years on the basis of convective cooling (Maaløe, 1974). The average crystallinity of the gabbro is 2000 and the total height of the layered series about 3400 m (Maaløe, 1976). From these figures the average accumulation rate F may be estimated as $F = 1{\cdot}691 \times 10^{-3}$/crystal sec.cm^2. With the average crystallinity of the gabbro at 2000, the average radius of the crystals is 0·492 mm. The radii of the primocrysts must have been smaller than this, as the primocryst core of the crystals of the gabbro constitutes about 50% by volume, and the average radius of the primocryst is estimated as 0·348 mm. The average sinking velocity of the primocrysts may be estimated using Stokes law, using the densities 3·0 g/cm^3 and 2·4 g/cm^3 for crystals and liquid, respectively (Wager and Brown, 1967). From these figures the sinking velocity is estimated as $2{\cdot}78 \times 10^{-4}$ cm/sec. As $F = vn$ where v is the sinking velocity and n the number of crystals per cm^3 in the magma, n may be estimated as 5·6 crystals/cm^3. Thus there were about 6 crystals/cm^3 in the magma just above the surface of the cumulate. The number of crystals in the topmost part of the magma chamber may have been small; assuming zero, then the average crystals per cm^3 would have been 3 and the average distance between the crystals is thus 0·7 cm. This distance appears to be small, but is still relatively large considering the diffusion rates of silicate melts.

It was shown by Nielsen (1964) that the composition around a sinking crystal with radius r is changed within a distance of magnitude r from the surface of the crystal. During settling the crystals will change the composition of the magma within a distance $2r$ from their centres, that is within a cross section of 0·4 mm^2. The composition of the magma will therefore have changed within a cross section of 1 cm^2 after 250 crystals have passed this cross section, or after about 1 mm of cumulate was formed. This figure is a minimum value as the primocrysts of a given mineral would have to change the composition of the magma a certain amount before the growth rates of other primocrysts will be changed. The thickness of the rhythmic layers is substantially larger, varying from centimetres to metres, and it may be concluded that the nucleation theory might be suggested as an origin of rhythmic layering. The present evaluation, however, does not prove the theory.

The nucleation theory. Relative variations in the total crystallization rate of two minerals, that is in the combined nucleation and growth rates, are not possible by thermodynamic equilibrium crystallization. A melt of eutectic composition, as point E in fig. 6, will remain at E by equilibrium crystallization. If the crystallization rate of say phase A is increased, then that of phase B will also have to increase in order that the composition of the liquid remains constant at point E.

Perfect thermodynamic equilibrium crystallization during the crystallization of melts is not to be expected as shown already by Gibbs (1876) from thermodynamic relationships (cf. Turnbull, 1956; Walton, 1969). The reason is the relatively high surface energy of subcritical nuclei compared to the free-energy difference between the nuclei and the melt. This thermodynamic treatment assumes the chemical potential of the nuclei to be the same as for a large crystal, which is not realistic as a very small assemblage of molecules has a chemical potential different from that of a large assemblage (Lothe and Pound, 1969). However, the difficulty for a silicate melt to nucleate is well known from experiments, and it is obvious that a certain amount of supercooling of a melt is required before any nucleation occurs (Chalmers, 1964).

At supersaturated conditions the crystallization of a melt will be entirely related to parameters like: the variation in nucleation rate with temperature and composition; the variation in growth rate with temperature; and the cooling rate and latent heat of crystallization. Of these, the variation in the nucleation rate is considered the major factor that might control the origin of rhythmic layering, while the others might influence the detailed features of the layering. The nucleation rate increases with decreasing temperature below the liquidus. In a small temperature interval just beneath liquidus, there will be no nucleation, thereafter the nucleation rate increases steadily until a maximum is reached at about $0{\cdot}9 T_l$, where T_l is the liquidus temperature in degrees Kelvin (Turnbull, 1956). The growth rate also increases with decreasing temperature just below the liquidus, but crystals nucleated will grow even at temperatures infinitesimally near to the liquidus temperature. The actual variation in growth rate with temperature may be of widely different functional types (Chalmers, 1964).

The crystallization relationships for a binary eutectic melt with crystalline phases A and B are shown in fig. 6 (Gordon, 1968). Phases A and B are stable beneath their liquidus curves L_a and L_b respectively, and nucleation starts at temperatures below liquidus temperatures at curves n_a and n_b. Under supercooled conditions, A and B are stable beneath the metastable extensions of their liquidus curves.

A cooling melt of composition M will form the first nuclei at p. If the cooling rate is fast the latent heat given off by the crystals will not be able to compensate the conductive heat loss, the temperature will be steadily decreasing, and the melt will be in the common nucleation field $n_a + n_b$. However, if

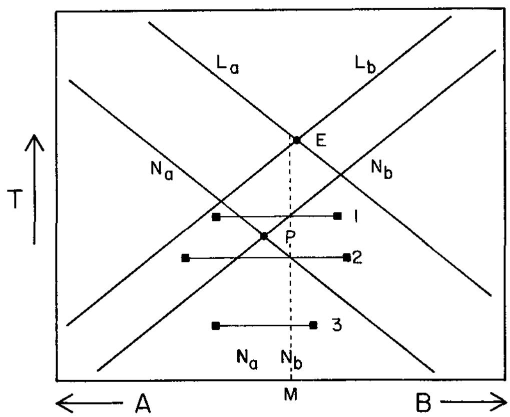

FIG. 6. Supersaturated crystallization in a binary eutectic system with solid phases A and B. L_a and L_b are the liquidus curves for A and B respectively. The nucleation curves for A and B are N_a and N_b respectively, by decreasing temperatures nucleation of A and B will start at these curves. Both A and B will nucleate at the common nucleation point P. Isothermal crystallization at 1 and 2 results in oscillatory nucleation while the nucleation rate for A and B may be nearly constant at 3.

the cooling rate is small the system may crystallize at nearly isothermal conditions, the result being an oscillating crystallization. At a slow cooling rate the crystallization of B will change the composition of the liquid at nearly isothermal conditions as shown at 1, that is the composition of the melt will vary relatively more than its temperature. The composition of the liquid will move towards A, because of growth of B crystals. During this movement B stops nucleating when the liquid crosses the curve n_b. The crystals of B already formed will continue growth as long as they are suspended in the melt, and the composition of the melt will intersect the curve n_a, whereafter A starts to nucleate. The crystallization of A then moves the liquid towards B and the process is repeated. The crystallization at 1 will result in the cumulate sequence b-a-b if the crystals are accumulating without overlap, otherwise the sequence will be b-a + b-a-a + b-b. If the liquid is cooling at 2, the sequence will be a-a + b-b-a + b-a. The binary example is simplified but demonstrates the main mechanism. The crystallization conditions of a magma may be adequately illustrated considering crystallization in a ternary system as shown in fig. 7. The main difference is that the temperature in a ternary or multicomponent system may decrease steadily during the oscillating crystallization. The heavy curve in fig. 7 shows the course of the liquid around the common nucleation curve, which is situated somewhere beneath a univariant eutectic curve not shown for clarity.

Both A and B are nucleating at 1, and the course of the liquid will be governed by the relative crystallization rates of A and B. If B is crystallizing faster than A the liquid will move towards A, and nucleation of B stops at 2. Thereafter the liquid will still move towards A because the suspended B nuclei and crystals still will grow. After some time the crystallization of A becomes dominant and the liquid moves towards B. By very small cooling rates the liquid will now move towards B, but this time the temperature will be higher than that of the common nucleation curve. The solid phase A will therefore stop nucleating at 3, and no nucleation occurs from 3 to 4, only the growth of A, which moves the liquid from 3 to 4. The course of the liquid has been assumed to be smooth in fig. 7.

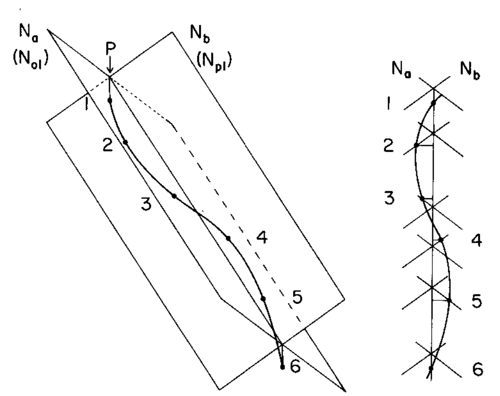

FIG. 7. Supersaturated crystallization around a common nucleation curve (P) in a ternary system. The univariant eutectic curve is situated above P but is not shown for clarity. The three-dimensional course of the liquid is shown in the left diagram, and the intersection points of this curve with nucleation planes is shown in the right diagram.

However, the liquid may move out into the region between 3 and 4, and the compositional movement then stops somewhere between 3 and 4. Nucleation would only start again after a drop in temperature. If A is growing in the liquid between 3 and 4, the nucleation of B will start at 4, and after some time at decreasing temperature nucleation of A starts at 5 whereafter A and B nucleate and grow in the melt, and the process may be repeated. If nucleation and growth rates and the latent heats of A and B are similar the suggested course of the liquid will not be possible, if so the liquid will move beneath the common nucleation curve all the time. However, minerals have different thermodynamic properties and their nucleation and growth will be different. The cumulate formed will display the sequence a + b–a–b–a + b. If A and B represent plagioclase and femic minerals respectively, the cumulate sequence will be plagioclase + femics–plagioclase–femics–plagioclase + femics, which is similar to that of the triple group. If A and B represents olivine and plagioclase respectively, the sequence is olivine + plagioclase–olivine–plagioclase–olivine + plagioclase, the sequence of the typical Skaergaard layering.

In more detail the typical rhythmic layering of the Skaergaard intrusion may be explained as follows. Mesocratic gabbro will be formed at 1 (fig. 7). The course of the magma onwards from 1 will be dependent on which mineral displays the highest crystallization rate. If it is plagioclase, the magma will move towards the n_p plane. At 2 the magma crosses this plane and the nucleation of plagioclase stops, but plagioclase primocrysts will still be suspended in the magma for some time, whereby the magma moves further away from the plagioclase composition. Plagioclase and olivine primocrysts will settle together for some time still forming mesocratic cumulate. The transition from mesocratic to melanocratic gabbro where olivine displays a high concentration will be sharp because the accumulation of plagioclase suddenly stops. Plagioclase primocrysts have been formed all over the magma chamber and when the primocrysts formed at the roof region have accumulated there will be no plagioclase left. After the plagioclase has settled out olivine will accumulate alone, and the composition of the magma will move away from the olivine composition and towards the n_{ol} plane (fig. 7). During this movement the growth rate of olivine crystals will decrease as the magma approaches the metastable extension of the olivine liquidus curve. After the liquid has crossed the n_{ol} plane at 3 no further nucleation occurs in the magma. From 3 to 4 olivine primocrysts are growing and settling, and the size of the primocrysts may still be decreasing as the metastable liquidus curve for olivine is approached. From 3 to 4 the magma will be cooled more rapidly than before as the crystallization of olivine is waning, and the magma may after a time intersect the n_{pl} plane, whereafter plagioclase begins to nucleate. Initially the nucleation of plagioclase will have a negligible effect on the temperature of the magma, but after some growth has occurred the decrease in temperature with time will become smaller. The transition from olivine to plagioclase cumulate may be abrupt or gradual, depending on the degree of separation of crystallization in time; some layering suggests an abrupt transition, while others display a gradual transition. The magma crosses the n_{ol} plane at 5, whereafter olivine begins to nucleate and crystallize. The growth of both olivine and plagioclase will decrease the cooling rate of the magma further, and the magma will move more or less parallel with the common nucleation curve as both primocrysts are crystallizing. The cycle will now be repeated after some crystallization and a new rhythmic layer will be formed.

The rhythmic layering of the Rhum intrusion consists of an olivine cumulate followed by an olivine + plagioclase cumulate, the allivalite. No leucocratic layer was formed except for some minor plagioclase bands, and the type of crystallization in the Rhum intrusion differed from that in the Skaergaard intrusion. Olivine was the initial primocryst phase during the formation of unit 14, and the magma was situated between 2 and 3 in fig. 7. However, the nucleation of olivine did not cease, as olivine also formed primocrysts during accumulation of the allivalite. The magma may therefore have moved back into the common nucleation field after olivine had crystallized for a period of time. The reason for the differences between the Skaergaard and Rhum intrusions is not clear, the composition of the Rhum primocrysts suggests a higher temperature of crystallization, which might suggest a faster cooling rate, but the heteradcumulus textures of the layered series of the Rhum intrusion suggest a very slow cooling rate (Wager and Brown, 1967). After both olivine and plagioclase began to crystallize together the allivalite was formed. For short periods plagioclase may have stopped nucleating whereby the fine-scale layering was formed, and olivine also stopped nucleating at times so that plagioclase accumulated alone. This crystallization behaviour suggests that the crystallization occurred very near the common nucleation curve. During the end stage of accumulation of the allivalite the magma may have been brought above this curve due to the latent heat lost by the two primocryst phases. Melanocratic fine-scale layering becomes more frequent at the very top of the allivalite layer, and the magma may have passed through the olivine nucleation field as it increased in temperature. No nucleation of olivine and plagioclase occurred for some time, and the thin chromite bands may have accumulated during this period. A subsequent decrease in temperature of the magma brought it into the nucleation field of olivine and a new cycle started.

The nucleation theory represented here may give a qualitative account for the origin of rhythmic layering, the substantiation of the theory requires experimental determinations of nucleation rates not presently available. Attractive features of the theory are the connotation of a relationship between the cooling rate of an intrusion and the formation of rhythmic layering, i.e. by fast cooling rates the magma will be in the common nucleation field all the time and no rhythmic layering will be formed. The different courses of the magma with respect to the nucleation planes can account for different types of layering. The supercooling required for the rhythmic nucleation to occur is evident from the reverse zoning of plagioclase primocrysts in the Skaergaard intrusion (Maaløe, 1976).

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