THE CRYSTALLIZATION OF SIMPLE PEGMATITES IN THE MOSS AREA, SOUTHERN NORWAY

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Maaløe, S.: The crystallization of simple pegmatites in the Moss area, southern Norway. *Norsk Geologisk Tidsskrift*, Vol. 54, pp. 149–167. Oslo 1974.

A brief description is given of the petrological relationships of the simple granite pegmatites of the Precambrian Moss area, southern Norway, and then an interpretation of their zoning, mineralogy and textural relationships on the basis of experimental investigations follows. The pegmatites crystallized under supercooled conditions, their large crystal size being governed by a separate gas phase (Jahns & Burnham 1958). Both these states came about because of a fall in the lithostatic pressure of a magma initially undersaturated with respect to water. The decrease in lithostatic pressure is assumed to have been a consequence of the intrusion of granite magma into dykes. It is suggested that graphic granite develops as a result of constitutional supercooling as explained in the text.

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Pegmatites of granitic composition differ in several respects from the medium-grained granites. The crystals are large, often display a pronounced zoning, and may contain a relatively high content of rare minerals. A very conspicuous feature of granitic pegmatites is the centrally placed quartz core, which may extend throughout the pegmatite dykes or be locally present as lensoid bodies. In general the crystallization of a granite magma governed by thermodynamic equilibrium first yields one phase, then two, and finally three solid phases. The development of a quartz core is therefore not possible when crystals form in this manner. These features, and others, distinguish pegmatites from granites, so one may therefore expect to find differences in the crystallization conditions.

Interpretation of the crystallization conditions of pegmatite magma depends on how the zoning and textural relationships are interpreted. Here the manner of crystallization will be considered first, thereafter the mineralogical variations will be interpreted and compared with those governed by equilibrium crystallization. Finally the more detailed crystallization kinetic relations between the different minerals will be considered, in particular development of the graphic granite texture.

Geological setting

The investigated pegmatites were classified as simple and exterior, and are situated 10-25 km north of a 120 km long and 30 km broad granite batholith in southeast Norway. The age of the granite is reported by Neuman (1960)

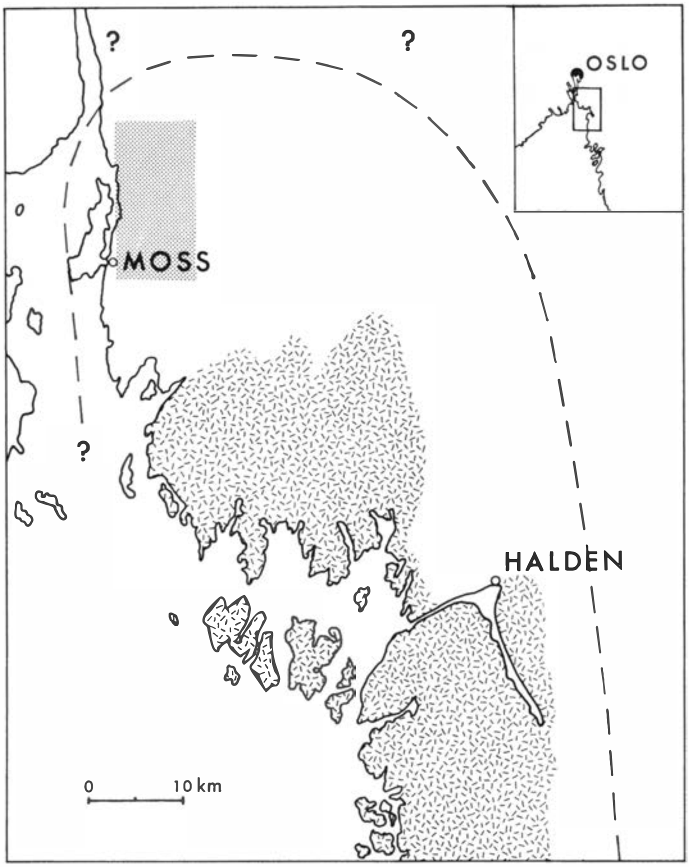

Fig. 1. Position of the investigated area. Stippled: exposed part of the granite batholith (the Østfold Granite), dotted: the investigated area, stippled line: possible extension of the granite batholith below the surface.

as around 800 m.y. Geophysical investigations and field relations suggest that the batholith is tabular in form and is believed to continue at depth below the investigated area (Fig.1) (Asklund 1947, Lind 1967, Ramberg & Smithson 1971). It should be emphasized, however, that Berthelsen's (1972, oral comm.) mapping of the Moss area suggests that the Bouguer anomalies should be cautiously interpreted, as the structure of the gneiss may have an important influence on the anomalies also. The interior pegmatites in the batholith are small (less than 1 m broad) and sparse, while those lying marginally and exterior may be up to 60 m broad and 1 km long. The general differences in size and frequency suggest that the marginal and exterior pegmatites are a different generation from those in the interior. This assumption is confirmed by the field relations at the contacts between granite and gneiss. The granite might well be completely devoid of pegmatites for hundreds of metres, while the overlying gneiss forming the roof of the batholith can be cut by closely-spaced dykes which appear to have been intruded synchronously with the granite magma. Generally the pegmatites in the investigated area have intruded during one generation, as far as may be judged from the field relations, although three dykes have been observed showing multiple intrusion. The pegmatite dykes occur in isolated swarms and not as single dykes which are typical of anatectic pegmatites (Fig. 2). (Ramberg 1955). There is a narrow

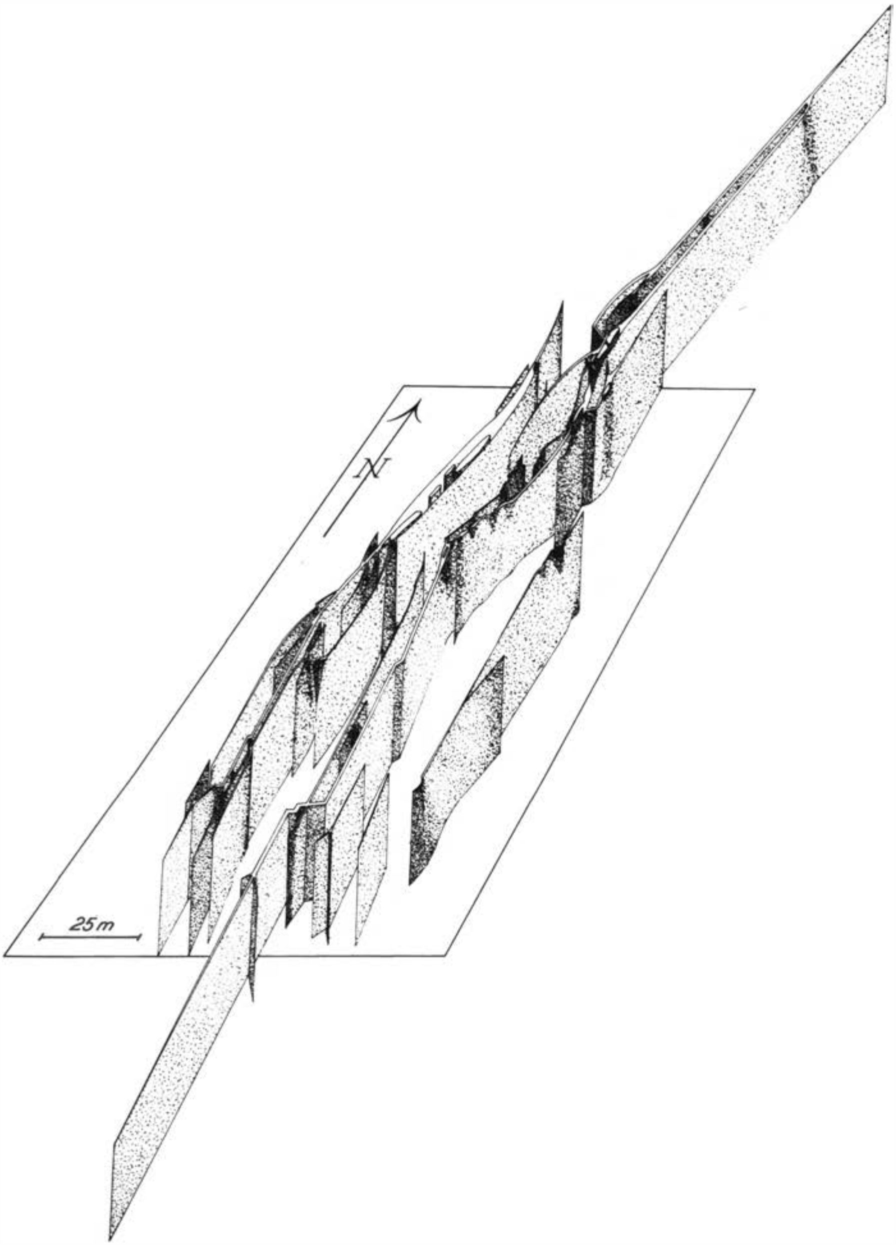

Fig. 2. A single dyke swarm showing the typical features of the swarms. The total dilation is largest at the central part of the swarm. Locality: 1 km east of the town of Moss.

zone of contact metamorphism (1-3 cm broad), where hornblende and biotite have chloritized, but felsic minerals are unaltered. The insignificant alteration suggests that the water content of the pegmatite magma was low, and that crystallization took place in a closed system.

Mineralogy and textural relationships

The mineralogy of the pegmatites and aplites is simple. The pegmatites consist of the essential minerals perthitic microcline, plagioclase and quartz in granitic proportions according to the definition given by Streckeisen (1967). Muscovite, biotite, spessartite garnet and beryl are accessories although the last named is quite rare. The pegmatites consist of three zones: a very fine-grained contact zone a few centimetres broad, an intermediate zone constituting the main-part of the pegmatites, and a central core zone containing the quartz core

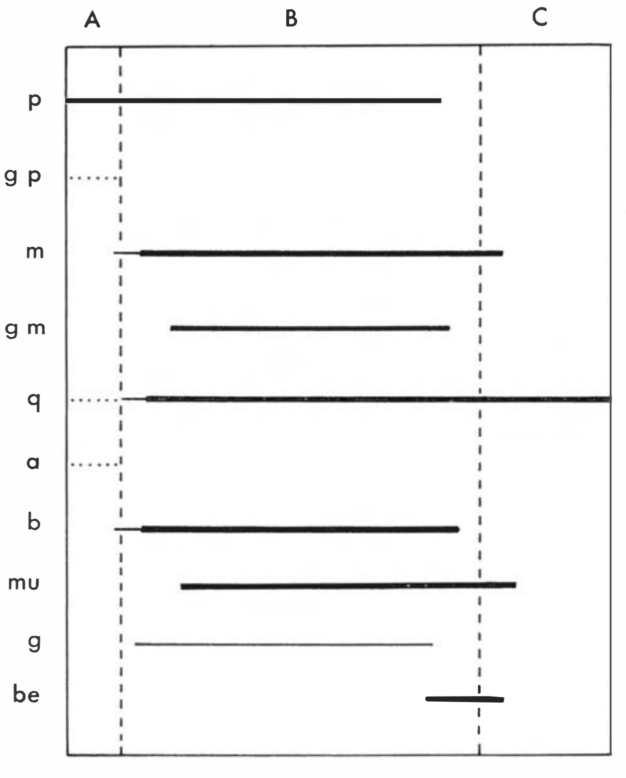

Fig. 3. The zoning displayed by most of the pegmatite dykes. A: contact zone, B: intermediate zone, C: central core zone. Signatures: dotted: fine-grained, thin line: medium-grained, thick line: coarse-grained. Abbreviations: p: plagioclase, g-p: graphic plagioclase, m: microcline, g-m: graphic microcline, q: quartz, a: apatite microlites, b: biotite, mu: muscovite, g: garnet, be: beryl. The crystallization of the pegmatites has occurred in a sedentary manner (see text). The zonal occurrence of a mineral therefore indicates the relative crystallization period of that mineral.

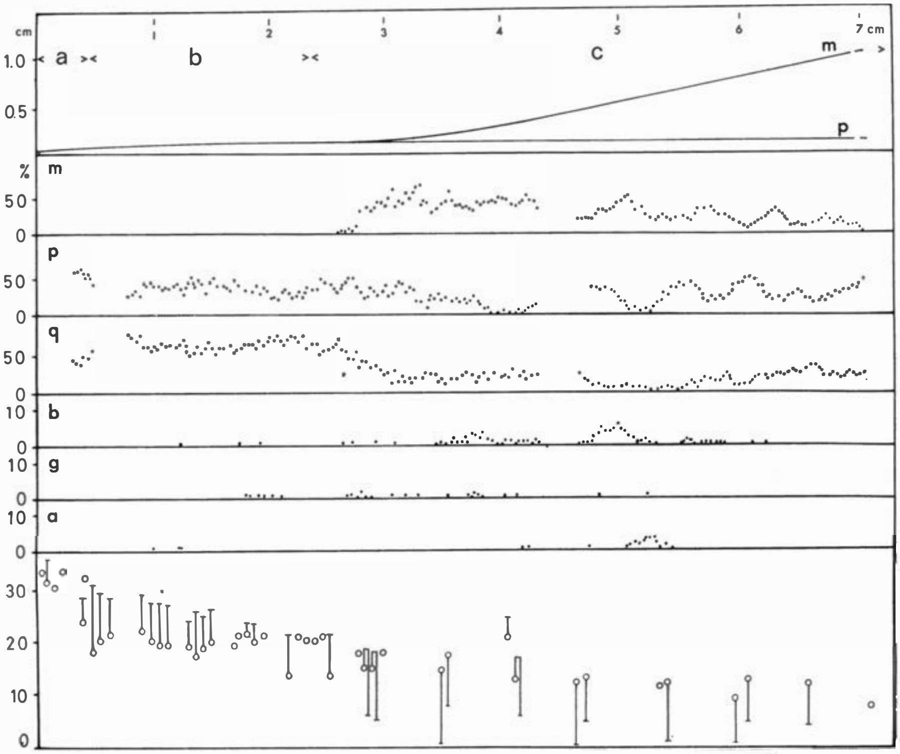

Fig. 4. The variations in crystal size, mineralogy and anorthite content as a function of distance from contact are shown (dyke no. 100). The represented variations are typical. Curves m and p in the top part of the diagram indicate the size variation for microcline and plagioclase respectively. In the middle part of the diagram, the dotted lines indicate the percentage distribution of minerals, m: microcline, p: plagioclase, q: quartz, b: biotite, g: garnet, a: apatite. The bottom of the diagram shows the variation in anorthite content. Circles indicate the composition of the cores of the plagioclase crystals, and the horizontal bars show the composition of the margins. Note the reverse in zonarity which takes place when microcline begins to occur.

and the surrounding microcline crystals (Fig. 3). The core zone does not occur in the smaller, less than 1 m broad dykes. But regardless of their thickness, all the dykes, whether pegmatites or aplites, have a characteristic contact zone about 1-3 cm broad. The zone is aplitic in texture and consists of only plagioclase and quartz (often in graphic intergrowth), and microscopic apatite microlites (Fig. 4). The transition between the contact zone and the proper pegmatoid intermediate zone is abrupt; the crystals change in size from about 1 mm to 1-5 cm over a distance of only 3 cm, while the intermediate zone itself has a rather constant crystal size. Simultaneously with the change in crystal size, microcline begins to occur (Fig. 4). The intermediate zones display conspicuous textural relationships; the microcline crystals, which average 5-10 cm in size, are constantly larger than plagioclase and quartz crystals by a factor of at least three and normally 10-25 by volume (Fig. 5). Microcline

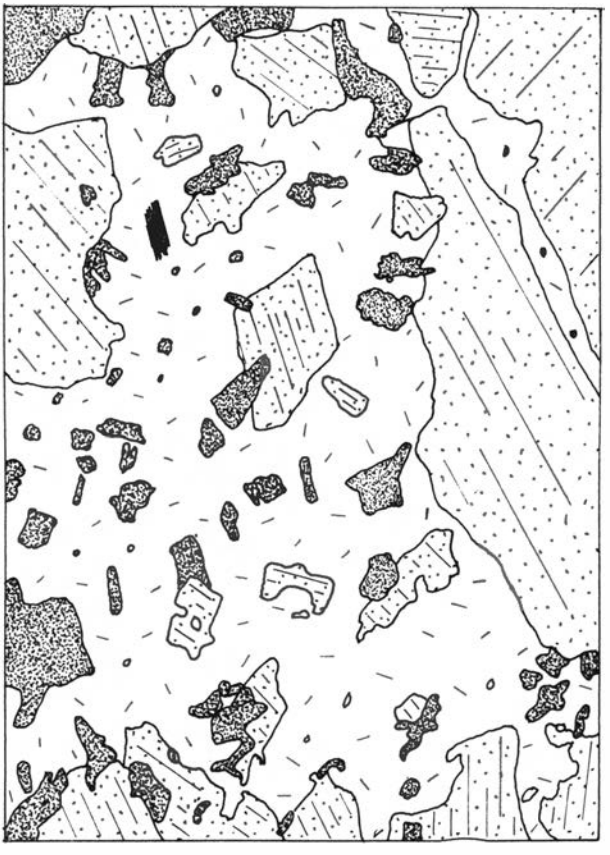

Fig. 5. Pegmatoid texture, half natural size. Open dotted: microcline, dense dotted: quartz, open stipples: fine-grained plagioclase, black: muscovite.

and quartz occur separately at the outer margin of the intermediate zone, while graphic microcline begins to occur 5-10 cm within the intermediate zone. The texture of the graphic microcline displays a characteristic variation with increasing distance from the contact; the distance between the microcline and quartz lamellae increasing towards the centre. The crystals of the essential minerals are anhedral, while biotite and especially garnet may be euhedral. The transition from the intermediate zone to the core zone is gradual, plagioclase ceases to occur and the microcline crystals become devoid of quartz inclusions. The quartz core is surrounded by 5-20 cm large microcline crystals which are euhedral towards it. The quartz core usually only consists of quartz, but muscovite and beryl may also be present.

The aplites also consist of microcline, plagioclase and quartz in granitic proportions, but differ in general from the pegmatites in not containing perthitic microcline and muscovite. The only accessory minerals are biotite and garnet. The aplites are very homogeneous rocks with a grain size of about 1 mm, and as they show no evidence of phenocrysts, one may suggest that the aplite magma intruded with a temperature at or above the liquidus temperature of the magma.

Crystallization types

Given the original composition of the magma it is possible to determine the crystallization sequence from the phase diagrams of the granite system (Tuttle & Bowen 1958, James & Hamilton 1969). The actual distribution of the crystallized minerals, or the zoning of the pegmatites, however, depends on how crystallization proceeds. The crystals may be developed either as fluentive or sedentary crystals, defined here as follows. *Fluentive crystals* are formed by the homogeneous nucleation of crystals freely suspended in the magma. They are named fluentcrysts and may be euhedral, but need not be so. *Sedentary crystals* are developed when the crystals grow out from the contact surfaces of the dykes towards the centre. They are developed by heterogeneous nucleation, and can not be completely euhedral. As the dyke cools progressively the sedentary crystals develop a common crystallization front moving towards its centre. When this happens the crystals are named sedentcrysts. The two types of crystal may to some extent be compared with those displayed by the Skaergaard intrusion. The plagioclase crystals of the perpendicular feldspar rock are truely sedentary, while the fluentcrysts may be compared with the primocrysts (cf. Wager & Brown 1968), which were formed as freely suspended crystals in the magma before accumulating on the bottom of the magma chamber. The fluentcrysts differ from the primocrysts by remaining stationary in the magma.

Drawing a distinction between the two types is important when considering the crystallization of the pegmatites. A sedentary crystallization would give rise to a fractionation towards the centre of the dyke, and the sequence of crystallization may be elucidated from the zoning of the pegmatite. With fluentive crystallization no directive fractionation occurs, and no well-developed zoning may be expected other than a cryptic one, e.g. the anorthite content of plagioclase crystals may vary with the distance from the contact. In the investigated pegmatites, quartz and microcline crystals are anhedral and does not give any indication of the type of crystallization. The type of crystallization must therefore be deduced from other features, e.g. from the presence of crystallization fronts, from the orientation of the crystals, and from geochemical features such as the K/Rb ratios.

By sedentary crystallization abrupt changes in the crystallization conditions may give rise to discontinuous changes in the mineralogy or texture, thus indicating the position of the crystallization front at the time the change took place. By fluentive crystallization no such front could be developed. About 10% of the dykes in the investigated area consist of alternating aplite and pegmatite zones, which are subparallel, conformable with the contacts and symmetrically distributed in the dykes. The transitions between aplite and pegmatite zones are abrupt, the crystals changing in size from about 1 mm in the aplitoid zones to 1-10 cm in the pegmatoid zones over a distance of 1-5 cm. If the zone nearest the contact is aplitoid, the boundary to the next pegmatoid zone is even (Fig. 6a); but if the outermost zone is pegmatoid the boundary

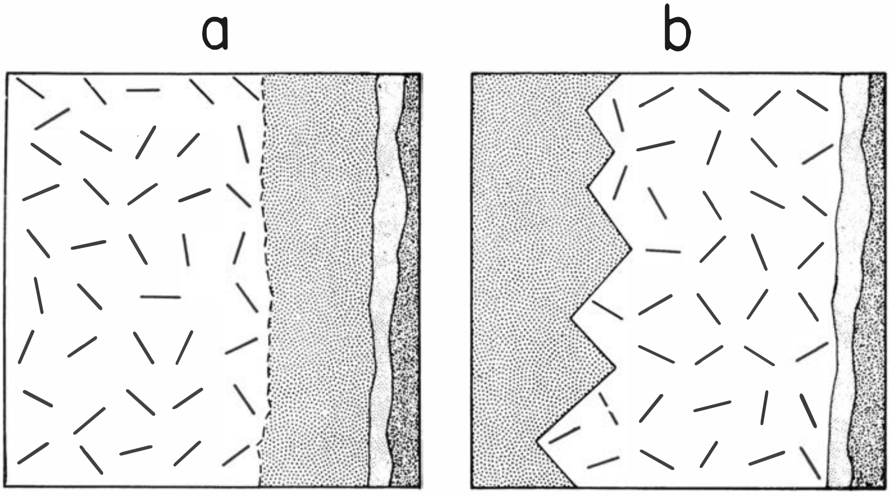

Fig. 6. Textural relationships between aplitoid and pegmatoid zones. Crystallization proceeds from right to left (see text). Open stippled: pegmatoid zone, medium dotted: aplitoid zone, light dotted: aplitoid contact zone, dense dotted: sidewall.

is determined by the shape of the pegmatoid crystals and becomes irregular with a jagged appearance (Fig. 6b). This difference may be understood if one assumes that the outermost zone is developed before the inner zones, since the structure of the boundary is determined by the outermost zone. Accepting this explanation the boundaries between the aplite and pegmatite zones represent crystallization fronts, and since such fronts may be developed only by sedentary crystallization, it may be concluded that the main part of the pegmatite, i.e. the minerals microcline, plagioclase and quartz, has crystallized in a sedentary manner. In many of the dykes crystals at the contact grow with an orientation perpendicular to it, and increase in size towards the centre. This feature represents further evidence of sedentary growth. Seden-

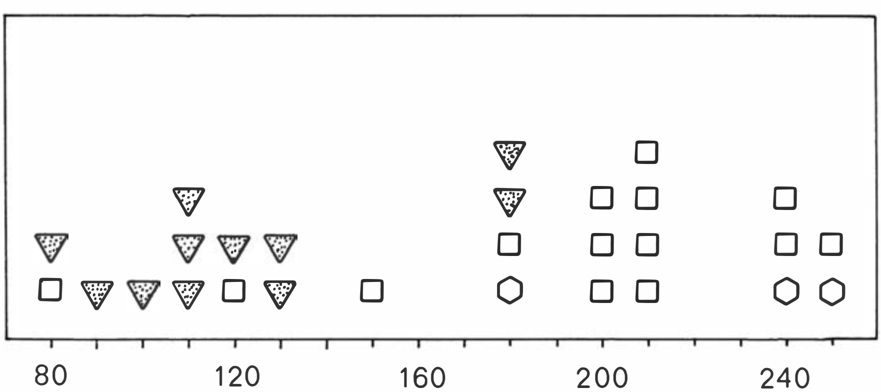

Fig. 7. Histogram showing the distribution of K/Rb ratios. Hexagons: granite, squares: aplite, triangles: microcline crystals from pegmatite cores. Ordinate: number of analyses with a given K/Rb ratio.

tary crystallization may give rise to a fractionation towards the centre of a dyke. The microcline crystals near the centre of the dykes should therefore display lower K/Rb ratios than the average ones. The K/Rb ratios for granites, aplites and for microcline crystals from near the quartz cores are shown in Fig. 7; the lower ratios for microcline crystals suggest a sedentary growth.

When crystallization proceeds with a temperature gradient, a planar interface is the most stable shape between liquid and solid phase (Chalmers 1964). Consequently the well-defined crystallization fronts observed in the dykes are in accordance with theoretical considerations. Since sedentary growth has occurred, the successive zones in a pegmatite dyke represent successive stages of the crystallization. This result allows the crystallization sequence to be investigated, and if the original compositions of the pegmatite magma is known and the thermodynamic equilibrium has been maintained, the zonal variation of a pegmatite may be predicted.

Composition of the pegmatite magma

Determination of the composition of the pegmatites is complicated by several factors. The texture and mineralogy of a single dyke may be quite constant,

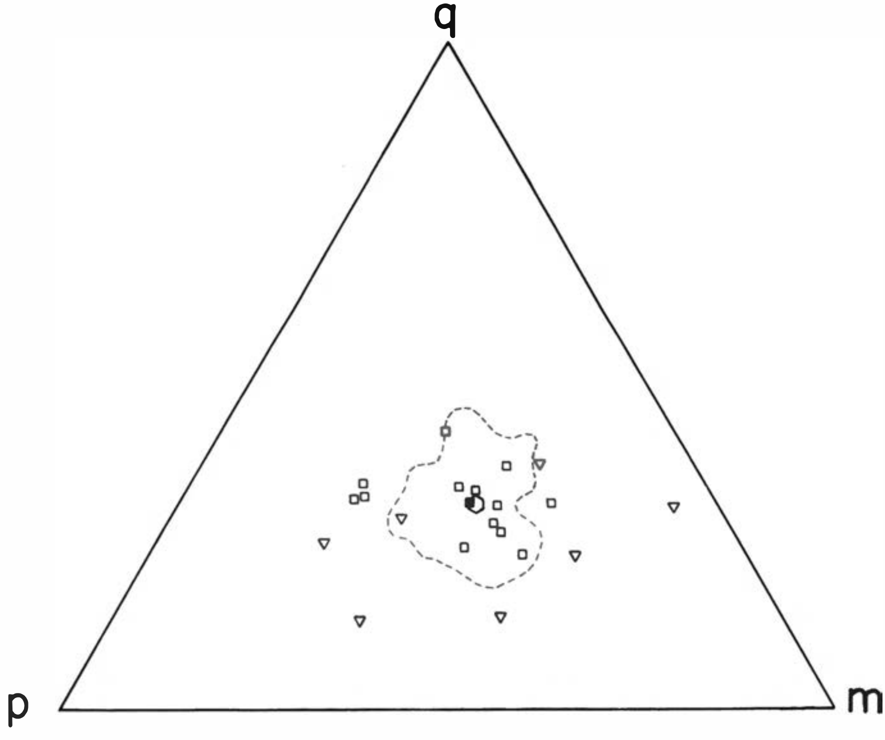

Fig. 8. Modal distribution of granites, aplites and pegmatites in the system plagioclase-microcline-quartz. Granite analyses (41) are within stippled area. Hexagon: average of granite analyses, squares: aplite, black squared: average of aplites, triangles: pegmatite. 38 granite analyses are from Asklund (1947).

but the proportions between the minerals vary too much along the strike for a single analysis to be representative of the whole dyke. A reliable modal analysis is possible only on fresh and flat surfaces, so out of 250 absorbed dykes only seven were found suitable for modal analysis. As shown in Fig. 8, the composition of the pegmatites shows considerable scattering, and they have a lower content of quartz than both granites and aplites. The analyses were made on relatively narrow dykes which may represent early solidified and differentiated parts of the pegmatite magma. The central parts of the pegmatite dykes contain quartz cores, and the early solidified parts of the dykes are therefore depleted in the SiO_2 component. The determined pegmatite compositions are therefore not representative of the composition of the pegmatite magma.

According to Jahns & Burnham (1969) the textural difference between aplites and pegmatites can be assumed to be determined by the absence or presence of a separate gas phase. Accepting this relationship the same type of magma may in a given area develop both aplites and pegmatites. Modal analysis of aplites are shown in Fig. 8 together with data on the granite. The average is nearly coincident with the granite average, in accordance with the previous assumption of an undifferentiated relationship between aplites, pegmatites and the granite. An exact determination of the composition of the pegmatite magma is impossible, but the close average for granites and aplites may be regarded as representative of the pegmatite magma.

Zoning

The average aplite contains 31.3% plagioclase, 35.0% microcline and 30.3% quartz. As the plagioclase has a composition of about An 15%, the aplites contain 4.8% anorthite, and the composition may be plotted with a good approximation in the An 5% plane in the system Ab-An-Or-Q-H_2O plane, which has been investigated by James & Hamilton (1969) at 1000 bars water pressure. The water content of the pegmatite magma was not necessarily especially high. The value may have been similar to that of the granite magma, as the granite magma forming the pegmatites intruded synchronously with the magma forming the batholite. The value of 1000 bars water pressure is assumed for the present calculation, but the results are not greatly influenced by the choice of water pressure. The albite content of the perthitic microcline is 16% and has been taken into consideration in the calculation below. Starting with a total amount of 100 g magma of aplitic composition, the zonarity may be calculated. The initial composition in the An 5% plane is ($Ab_{35.3}Or_{31.7}Q_{33.0}$). As seen from Fig. 9 such a composition first crystallizes plagioclase until the intersection point at ($Ab_{23.2}Or_{37.8}Q_{39.0}$) is reached, after which plagioclase is joined by Al-feldspar. Finally plagioclase, quartz and Al-feldspar crystallize together at ($Ab_{22.0}Or_{36.0}Q_{42.0}$). The resulting zonal variation is shown in Fig. 10e and should be compared with observed zonarities shown in Fig. 10a, b, c, d. In all the observed cases two solid phases crystallized immediately after the intrusion followed soon after by microcline. Consequently it can clearly be seen that any theoretical predictions based on equilibrium crystallization are inconsistent with the observations. At least two, and probably three phases were below the solidus temperature as soon as crystallization began, and this could only have been possible by supercooled crystallization. Crystallization of the pegmatite dykes concluded with a phase (a quartz core) when the dykes are at least 1 m broad giving the crystallization sequence of 2-3-1 solid phases; in contrast to thermodynamically governed crystallization which, whether fractionated or not, gives a sequence of 1-2-3 stable solid phases. The pegmatite magma originating from the granite magma must therefore have been below the solidus temperature at or just after the intrusion. In contrast, the temperature of the aplite magma was suggested above the liquidus temperature.

Zonarity of plagioclase

The supercooled crystallization is further illustrated by the zonarity of the plagioclase, which in general varies in a remarkable manner as a function of distance from contact (Fig. 4). The shape of the liquidus and solidus curves for the albite-anorthite system does not change essentially from one to 5000 bars water pressure (cf. Bowen 1913, Yoder et al. 1957). The inverse zonarity cannot therefore be explained by pressure variations. This type of zonarity

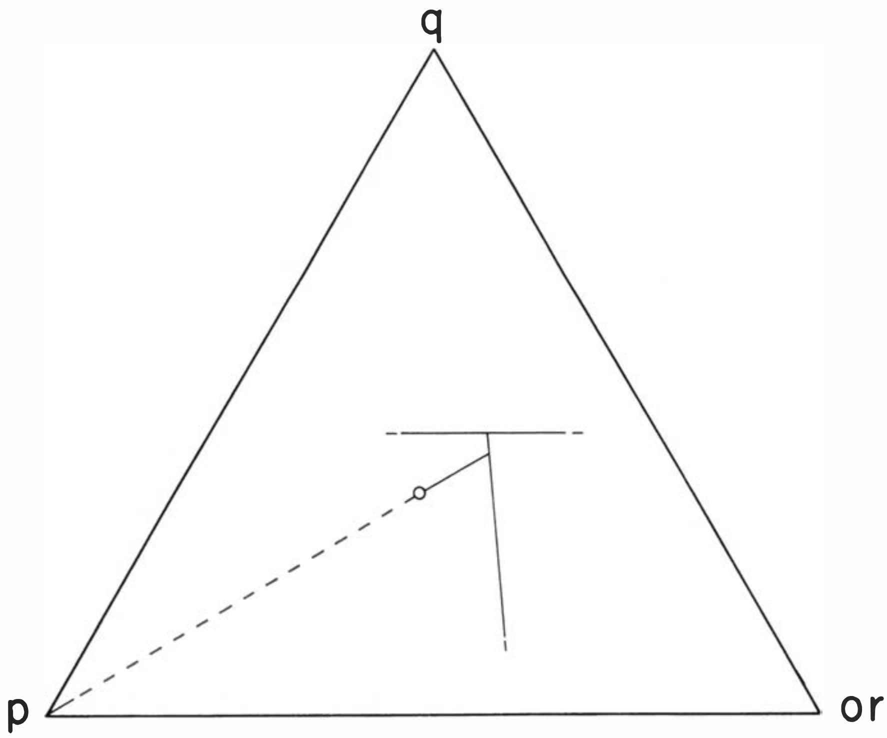

Fig. 9. The system Ab-An-Or-Q-H_2O in the An 5% plane at 1000 bars water pressure, circle: average of aplite analyses.

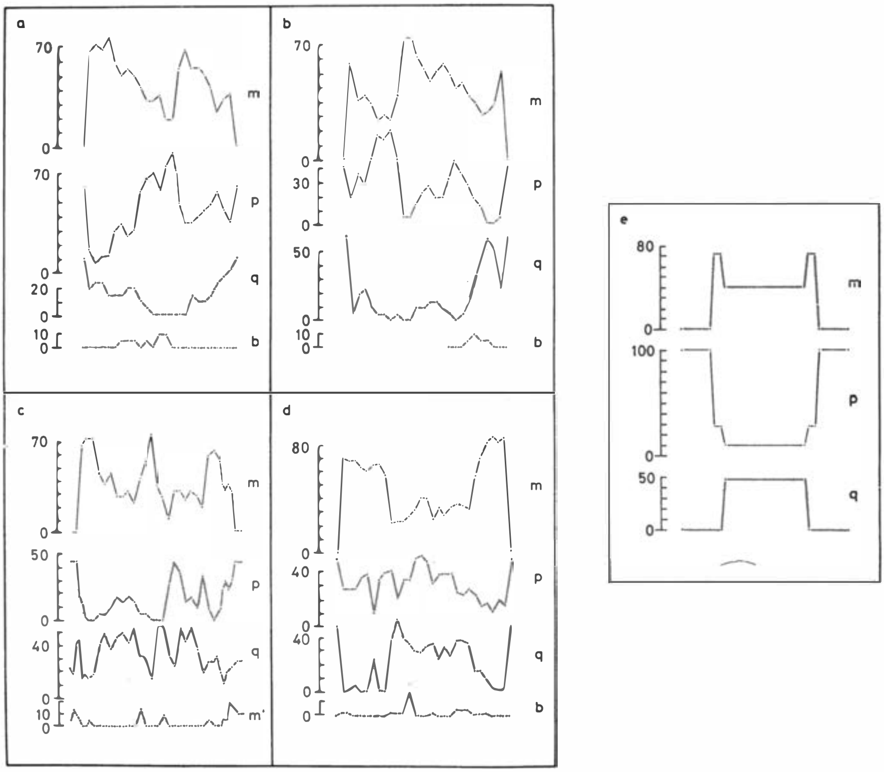

Fig. 10. Observed (a, b, c, d) and calculated zonarities; p: plagioclase, m: microcline, q: quartz, b: biotite, m': muscovite. The analyses were carried out as proposed by Berthelsen (pers. comm.) by counting parallel to the contact. Between 600 and 800 points were counted for each of the diagrams.

is only possible by supercooled crystallization in a magma of constant composition. The typical variations shown in Fig. 4 may be explained somewhat speculatively as follows. The changes in zonarity could be due to the relationship between the cooling and crystallization velocities. The first crystals at the very contact may have crystallized at or near equilibrium – area a (Fig. 4) – just after the instrusion of the magma. The temperature falls very rapidly at the contact of a dyke (Jaeger 1968), and the next crystals to form therefore crystallizes with a lower anorthite content than the first ones – area b; but as crystallization advances under supercooled conditions, the temperature around these crystals rises and the anorthite content with it. As the temperature cannot go above the liquidus temperature, the anorthite content at the margins of the crystals cannot be greater than at a. This condition is fulfilled in all the investigated cases. The temperature falls more slowly away from the contact and crystallization is therefore relatively fast in relation to that of cooling, so that crystals with normal zonarity develop – area c. The fine grained texture of the contact zones gives the appearance of chilled border zones. The supercooled crystallization of these zones provides evidence of a supercooled crystallization of the pegmatite magma from the beginning of its crystallization.

Cause of supercooled crystallization

If the present explanation for the modal and cryptic zonarity is accepted, one may ask why the pegmatite magma crystallized by supercooled conditions. Experiments by Burnham & Jahns (1958) indicate that pegmatoid textures are developed in the presence of a separate gas phase. Two processes may cause the development of a separate gas phase in a granite magma initially

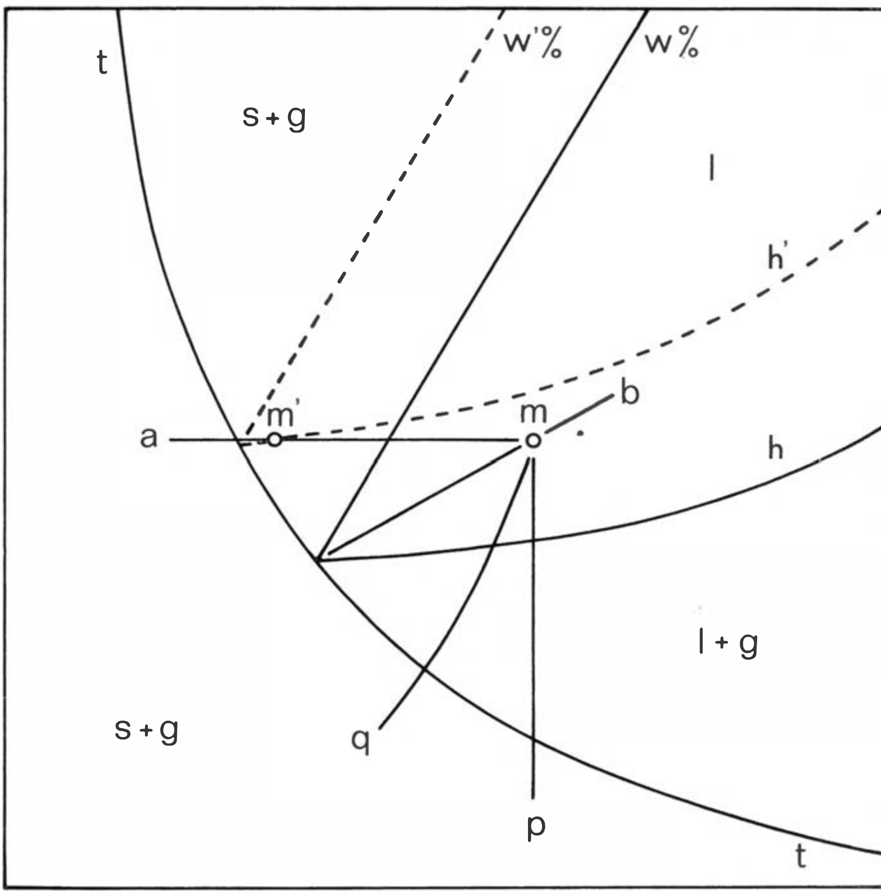

Fig. 11. P–T diagram showing the conditions for aplite and pegmatite development by fractionation (stipples) and decrease in pressure (full-drawn line), partly from Fyfe (1970). Symbols: m: initial condition of the magma, t: the ternary minimum curve for the water-saturated granite system, w: the solidus curve for a magma containing w% water, h: the water pressure in a magma containing w% water, b: this line separates the P–T fields for aplite and pegmatite development, m-a: aplitoid crystallization, m-p: pegmatoid crystallization, m-q: pegmatoid crystallization by a simultaneous fall in temperature and lithostatic pressure.

undersaturated with respect to water. Recent experiments by Piwinskii (1968) and Robertson & Wyllie (1971) suggest that granitic magmas in general crystallized by an undersaturated water content (Wyllie 1971). An undersaturated granite magma such as m (Fig. 11) may become supersaturated by either an enrichment of water by differentiation (Jahns & Burnham 1969) or by a decrease in lithostatic pressure. By differentiation the temperature of the magma decreases simultaneously with the increasing water content. The P-T conditions for the magma move along the line m-m′, while the water content increases above w′ %. The magma will vesiculate as soon as the water content is above w′ %, and a pegmatoid crystallization condition has been obtained.

The field relations in the investigated area as well as the coincidence in the compositions of aplites and granites do not suggest that the pegmatites developed from a differentiated granite magma. Vesiculation of an undersaturated granite magma may occur also if the lithostatic pressure is lowered below the hydrostatic pressure. With a decrease in lithostatic pressure, an undersaturated magma such as m will become supersaturated with respect to water when the lithostatic pressure is lowered below the saturation curve h. If the lithostatic pressure decreases further the P-T conditions of the magma reach point p. After crossing the curve t, supercooled crystallization occurs in an already vesiculated magma, and the crystallization conditions for the investigated pegmatites have been obtained. The required fall in the lithostatic pressure may have come about when the granite magma intruded fractures in the gneiss overlying the batholith. A sufficient fall in lithostatic pressure may therefore develop both vesiculation and supercooled crystallization conditions.

Kinetics of crystallization

The final texture of a crystallizing mixture of solid phases is determined by two independent processes – nucleation and growth. The relative importance of these two processes must be estimated as far as possible in order to explain the texture of the pegmatites or any other rock.

In the aplites all the minerals have about the same crystal size (1 mm), while in the pegmatites the microcline crystals are consistently larger than the other minerals. The texture of the aplites and pegmatites therefore differ by two phenomena; (1) the crystal size of the pegmatites is larger than that of the aplites and (2) the crystal size of microcline is larger than that of the other minerals in the pegmatites, while the crystal size of microcline in the aplites is similar to that of the other minerals. The pegmatoid crystallization condition – the vesiculation of the magma – therefore not only results in a large crystal size in general; but especially favour the development of large microcline crystals. The contact zones of both aplites and pegmatites consist entirely of fine-grained plagioclase and quartz. After the initial crystallization of the contact zones, plagioclase, quartz and microcline must have the same crystallization kinetic properties by normal crystallization conditions, as they have about the same crystal size in both aplites and granites. The presence of plagioclase and quartz in the contact zones should therefore not be attributed to a high nucleation velocity in general, but to a higher nucleation velocity than that of sanidine in supercooled conditions (sanidine inverts to microcline). The larger amount of single plagioclase and quartz crystals in the pegmatites is therefore because of the relatively larger nucleation velocity of these two minerals than that of sanidine in supercooled conditions. The relatively large crystals size of microcline in the pegmatites is therefore governed by a slow nucleation velocity and a high growth velocity. The growth velocity is mainly determined by diffusion, so consequently potassium and sodium ions should have a high diffusion velocity in pegmatoid crystallization conditions. The experimental investigations by Burnham & Jahns (1958) indicate that sanidine actually crystallizes with a larger crystal size than the other minerals in the presence of a separate gas phase. This is in accordance with the experimental works by Orville (1963) and Adams (1968), which indicate that the solubility of potassium and sodium in a gas phase is high, while that of calcium is low. The large crystal size of microcline in relation to that of plagioclase may thus be due to the high solubility of sodium and potassium in a separate gas phase, where the diffusion rates are high compared to a silicate melt.

Origin of graphic granite

The pegmatites contain two types of graphic granite. The contact zones have exclusively a graphic plagioclase, while the pegmatoid zones have exclusively the well known graphic microcline. The texture of the graphic microcline varies in a systematic manner with the distance from the contact. At the nearest point to the contact, graphic microcline consists practically entirely of aphanitic tabular lamellae of microcline and quartz. Towards the centre of the dyke, the distance between lamellae gradually becomes larger. When it is about ½-1 cm, the texture changes with the quartz lamellae becoming acicular inclusions with a hexagonal cross-section in the microcline. Further inside the dykes the inclusions first become cone shaped and then form lumpy masses in the microcline, after which the two minerals crystallize separately with a crystal size of about 5 cm. Just before the quartz core, microcline occurs without quartz inclusions as well as quartz is totally absent between the microcline crystals, while microcline is absent from the core. On the whole there is a gradually increasing separation of the two minerals with distance from the contacts.

The origin of graphic granite has been explained in various ways. Brøgger (1881), who first investigated the pegmatites in the Moss area, proposed, on textural grounds, that the crystallization of microcline and quartz had proceeded simultaneously. This origin was later doubted and a replacement theory was proposed by several authors (cf. Jahns 1955). Experimental work (Schloemer 1962) has supported Brøgger's ideas, and further the combination striations seen on the lamellae is evidence of simultaneous growth. As a result of experimental work, Rutter & Chalmers (1953) found that the development of cellular substructures, identical to graphic ones, was by constitutional supercooling. A necessary condition for the occurrence of constitutional supercooling is that the melt must consist of at least two components, and that the crystallization must proceed along a temperature gradient. Both these conditions are fulfilled for the pegmatite magma crystallizing in a dyke. Imagine a binary melt consisting of two components A and B, with A being the first to crystallize. The situation is shown in Fig. 12. As A crystallizes the amount of B in the melt increases in front of the interface, and independently of the distribution coȩfficient the liquidus temperature in front of the interface would fall in relation to the liquidus temperature in a greater distance (a). The liquidus temperature at the interface is thus lower than in the bulk liquid. The system is stable at the two points x and x′, but between these points the system is supercooled as the actual temperature is lower than the liquidus temperature. If a small perturbation occurs as shown on (c), this would grow further inside the liquid and make a protuberance (d). The protuberance could grow until point x′ where equilibrium would once more be obtained. The accumulation of B around the protuberance retards solidification in this region and consequently it cannot expand laterally. In a natural system several perturbations will occur and the protuberances will develop beside one another (e). The ideal form of the protuberances is lamellar, but the melting entropy and the cooling velocity have an important influence on the texture of the crystallizing system. Investigations by Hunt & Jackson (1966) and Kerr & Winegard (1967) have shown that if both solid phases have a low melting entropy the graphic structures will be lamellar, and if one of the phases has a high and the other a low melting entropy, the structures will be more irregular. When both phases have a high melting entropy they will crystallize separately. The later condition also favours a euhedral habit of the crystals. The actual components have the following melting entropies (Robie & Waldbaum 1968): quartz – 0.976 cal/K°mol; sanidine – 9.980 cal/K°mol; albite – 9.740 cal/K°mol. The feldspars have melting entropies which are about ten times higher than those of quartz. From these figures one would expect sanidine and plagioclase to crystallize separately, as is always the case, and the differences between the melting entropies of feldspar and quartz indicate that graphic textures are possible, in accordance with the occurrence of both graphic microcline and plagioclase. Small temperature gradients favour acicular rather than lamellar textures (Hunt 1968), in accordance with the occurrence of acicular

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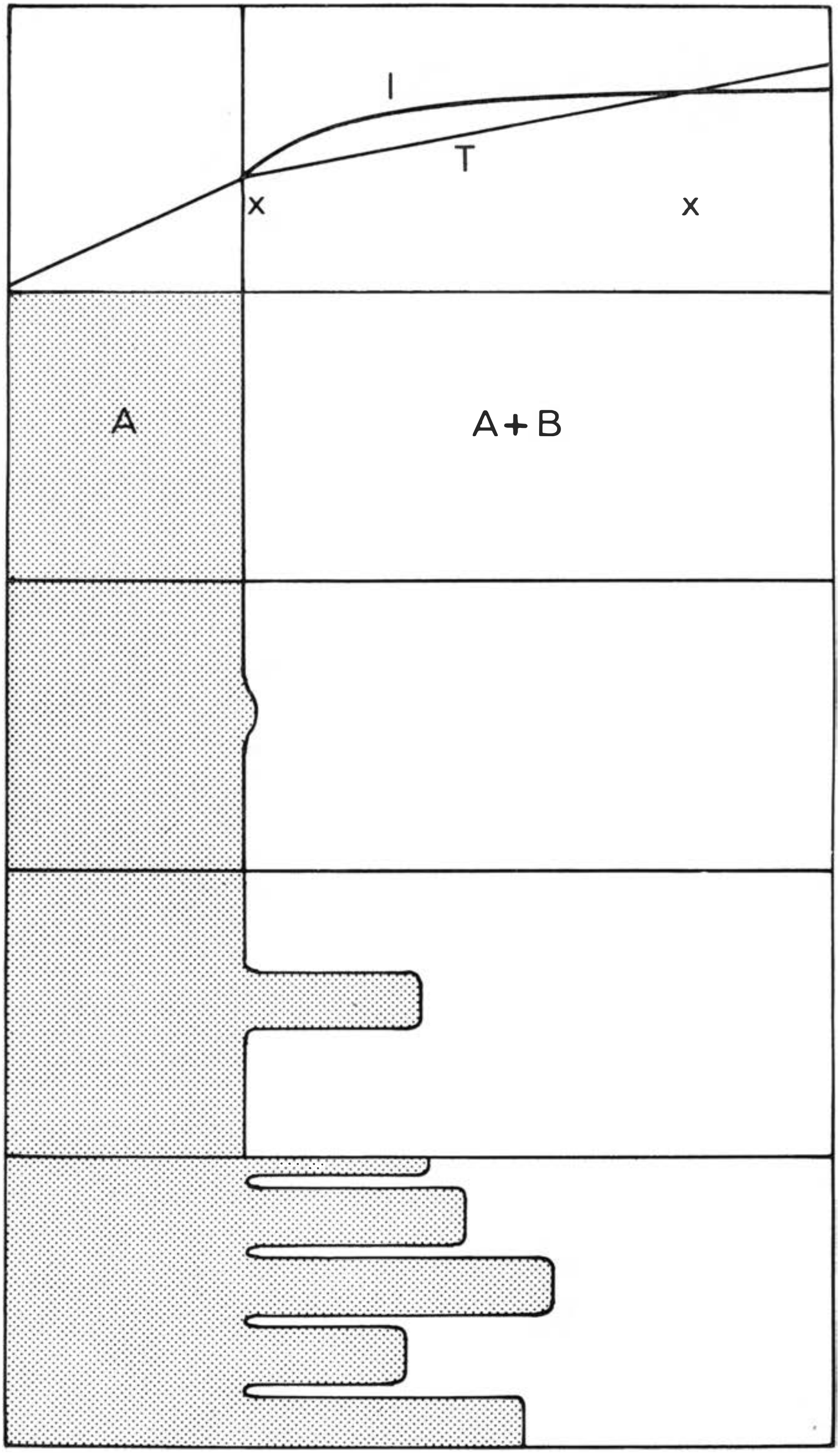
Fig. 12. Development of graphic textures. Solidification proceeds from left to right. Stippled: solidified A component, white: liquid mixture of A and B component, 1: liquidus curve for A in melt, T: temperature of solid and liquid. The liquidus temperature for A increases in front of A, as a result of the increasing amount of B in front of A.

a
b
c
d
e



textures further inside the dykes than lamellar ones. It was demonstrated from different conditions by Jackson & Chalmers (1963) and Tiller (1958), that the width of the lamellae w is proportional to $R^{-1/2}$, where R is the velocity of the crystallization front. This relation further supports the development of graphic granite by constitutional supercooling, as the width at the contacts is less than a millimetre and from ½ to 1 cm in the central parts of the dykes.

If the cooling velocity is low enough, a complete separation of the two components may occur, as seen in the case of the quartz core. As discussed above, the marginal position of microcline in relation to quartz along the core is due to the high crystallization velocity of microcline. The generally euhedral habit of microcline towards the quartz core may be caused by the relatively high melting entropy of sanidine. Plagioclase occurs in the contact and intermediate zones, but has not been observed with microcline in the core zone (Fig. 3). The development of crystals by supercooled crystallization conditions depends on kinetic properties; the relatively early crystallization of plagioclase may therefore be due to the high nucleation velocity by supercooled conditions.

Acknowledgements. – The author is greatly indebted to Professor A. Berthelsen for his encouragement, inspiration and many valuable suggestions. Prof. H. Sørensen, Dr. C. K. Brooks and Dr. N. B. W. Harris kindly commented on the paper. The author was introduced to the area by Dr. E. Skou-Jensen, and discussed the paper with T. Haaland and S. Petersen. The author was introduced to atomic absorption and X-ray fluorescence methods by Dr. O. Larsen and Dr. E. Leonardsen.

November 1972

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