TEXTURAL FEATURES OF SOME CONTRASTED IGNEOUS CUMULATES FROM SOUTH GREENLAND

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CONTENTS

Abstract.

Five particular occurrences of layered plutonic rocks within the south Greenland alkaline province are discussed. These five examples are of gabbro, anorthosite, syenite of larvikite-nordmarkite type, foyaite and eudialyte nepheline syenite, respectively. Each is thought to consist of cumulate rocks formed by bottom accumulation of the early mineral phases and the subsequent crystallization of the trapped interstitial liquid. The possible causes of banding and feldspar lamination are considered in each case. The presence or absence of feldspar lamination is used as one criterion for deciding whether the settling of the early (cumulus) phases occurred through moving or still magma. Magmatic flow during the accumulation of the cumulus mush was important in controlling the degree of packing within the latter and hence was influential in determining the ultimate bulk composition of the solidified rock.

PREFACE

In the course of four seasons mapping in south Greenland as a member of the Greenland Geological Survey, the author has had the opportunity to become acquainted with a number of layered intrusions of Pre-Cambrian age. Within these, there occur various textural and structural similarities, irrespective of the differences in composition: the rock types include gabbroic, foyaitic, syenitic and even granitic varieties. Whereas much has been published on the textural characteristics of layered gabbroic and ultrabasic rocks, comparable accounts for alkalic and granitic rocks are scarce. In this paper the author attempts to apply some of the recent ideas on layered basic rocks advanced by WAGER, BROWN and WADSWORTH (1960), to the interpretation of some selected occurrences within these south Greenland layered intrusions and to show that they have an application not only to the problems of basic intrusions but also to those of the syenitic assemblages.

Field and laboratory research is being actively pursued in the case of practically all the intrusive complexes in the Ivigtut-Julianehåb region by the Greenland Geological Survey and a great body of new information is to be expected within the next few years. The author had the privilege to accompany Dr. C. H. EMELEUS in the field for much of the re-mapping of the Grønnedal-Îka complex and is indebted to him for his cooperation over the section of this paper dealing with the Grønnedal-Îka foyaites. Further thanks are also due to professor L. R. WAGER and Drs. G. M. BROWN and EMELEUS for critically reviewing the manuscript and for their contributions and suggestions.

The section concerning the kakortokites is partly based on the classic description of N. V. USSING's and partly on some observations made during a brief visit to the area in 1959. The visit was made possible through the courtesy of Mr. J. FERGUSON who is at present engaged on a detailed reinvestigation of the southern part of the Ilímaussaq complex.

The author gratefully acknowledges the help and resources of the Greenland Geological Survey, under the direction of Mr. K. ELLITSGAARD-RASMUSSEN.

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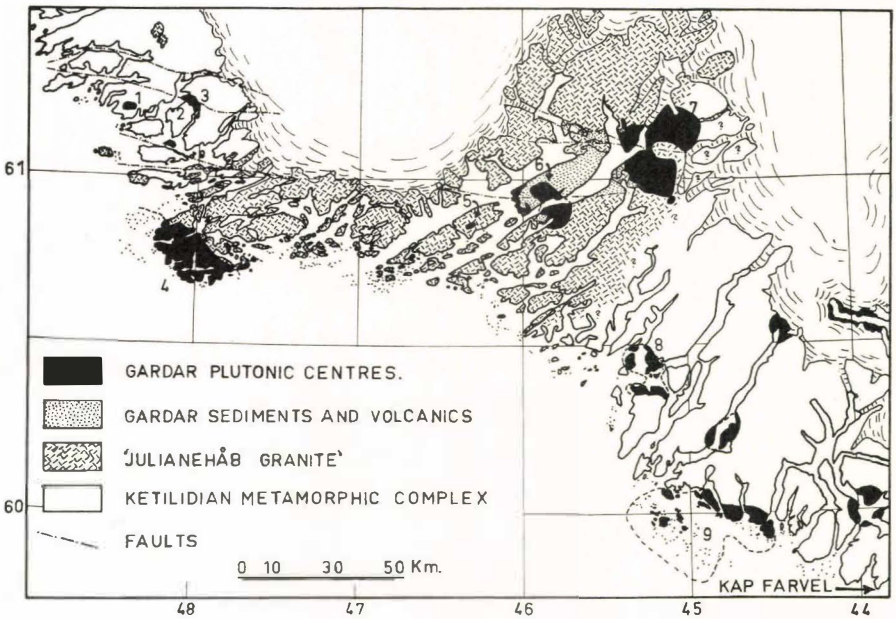

Fig. 1. Sketch map showing the location of the main plutonic igneous centres in south west Greenland. 1, Kûngnât; 2, Ivigtut; 3, Grønnedal-Íka; 4, Nunarssuit; 5, Tugtutôq; 6, Ilímaussaq; 7, Igaliko; 8, Frederiksdal; 9, Sydprøven. (Map compiled by A. Berthelsen).

INTRODUCTION

A considerable number of Pre-Cambrian intrusions occur in south Greenland, where they are found cutting the basement granites and metamorphic rocks and also the volcanics and sediments of the Gardar continental period (see Wegmann 1938). Among the main rock-types represented at the various centres are gabbros, nepheline syenites, saturated syenites (grading from larvikitic to nordmarkitic types), and alkali-granites. Many of the individual intrusions, especially the larger ones, have been found to possess internal layering as shown by contrasted mineral banding or by the preferred orientation of the early minerals. At Kûngnât, where the banding in basic syenites of larvikite affinity shows a confocally directed inward dip, small discordances in the attitude of the banding are suggestive of current-bedding. Furthermore, trough-like features in the syenite, defined by layers of mafic rock, recall the trough-banding at Skaergaard (Wager and Deer, 1939) and are taken as convincing evidence that strong, locally confined currents were set up in the cooling magma, (Upton, 1960). Similar features have since been noted at other centres (Pulvertaft, GGU report 1958.

Harry and Emeleus, 1960), and it is apparent that the intrusive magmas in this alkaline province possessed high mobility which permitted not only extensive gravitative crystal differentiation, but which also allowed current activity, probably convective circulation, to play an important part within the cooling magmas.

Analogous structures and textures developed within the layered sequences of some contrasted intrusive rocks leads to the conclusion that each of these sequences evolved through a common process. They are believed to represent gravity accumulated piles of early minerals, cemented by the crystallization of the interstitial magma trapped within the crystal mush. Where mineral banding is present it is thought to be due to periodic crystal sorting by magma currents and to repeated variations in partial pressure of water vapour dissolved in the magma; these processes working either independently or concurrently. The relative importance of these two processes varied considerably from centre to centre. A further mechanism, dependent upon the relative case of nucleation of the early minerals, as suggested by Wager (1959), may also have been contributary to the production of the banded rocks. In a recent paper (1960), Wager, Brown and Wadsworth introduced a revised terminology for igneous rocks formed through crystal accumulation which will be used in this account. They propose that 'cumulate' be used as a general name for rocks originating in this way. A 'cumulus crystal' (= a 'primary precipitate' crystal (see Wager and Deer 1939 p. 127)) is defined as "... a unit of the pile of crystals as originally precipitated from the magma before any modification by later crystallization". The material added to the cumulus after its sedimentation, together with any new mineral phases which may have appeared during the crystallization of trapped interstitial liquid was described as the 'intercumulus'. The rocks described below are: 1) the gabbros which outcrop as a great branching dyke system to the west of the Ilímaussaq complex, 2) the layered anorthosites which are brought up as included masses within the gabbro body, 3) the layered syenites which occur as a stock-like intrusion forming the western half of the Kûngnât complex, 4) the foyaites in the north-western part of the Grønnedal-Íka region, and 5) the kakortokites (eudialyte-rich nepheline syenites) occurring in the southern sector of the Ilímaussaq complex.

In these rocks the dominant cumulus mineral was, in each case, feldspar. These feldspars were not greatly modified by intercumulate growth and they have generally retained an idiomorphic habit. The habit is tabular, parallel to (010) and the most extreme development of this habit is seen in the foyaites of the Grønnedal-Íka district where crystal growth along the *b* direction was severely inhibited. The tabularity is not so pronounced in the Kûngnât basic syenites as in the kakortokites and gabbroic rocks, and it appears that loss of tabularity may be correlated with increasing SiO_2 content of the magma. Thus in the quartz syenites at Kûngnât the crystals are generally elongate parallel to *a* but show little flattening and often show approximately square cross-section parallel to (100).

Investigation of these rocks has suggested the possibility that the presence or absence of magmatic flow during the deposition of the cumulus can be a factor leading to diversity of rock type, even before current action becomes vigorous enough to effect any winnowing of the

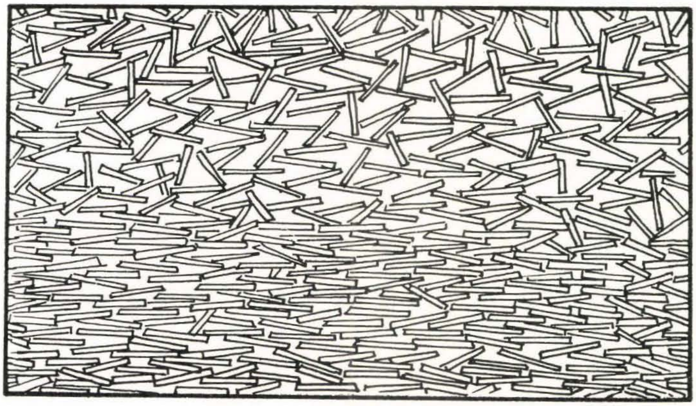

Fig. 2. A diagrammatic vertical section through an unmodified feldspar cumulus deposited during gentle flow (lower part), and during quiescence, (upper part).

cumulus into heavy and light fractions. This is a consequence of the different degrees of packing that can be obtained within a cumulus consisting mainly of tabloid feldspars under differing conditions of quiescence and flow. The arrangement of the feldspar crystals is held to be a critical factor in determining the volume of the intercumulus liquid. In those cases where the cumulus feldspar is markedly tabular, disorderly settling under the influence of gravity alone would lead to a high ratio of intercumulus to cumulus. On the other hand, where the feldspars are close packed by the action of mild currents and the resultant rock shows better alignment and parallelism of the feldspars, then the intercumulus/cumulus value is low. The two conditions are illustrated diagrammatically in fig. 2 which represents a cumulate in which feldspar was the sole cumulus mineral. The upper portion represents formation in still conditions and the lower portion represents accumulation during flow. Actual examples of such rock types can be found in the Tugtutôq anorthosites and in the perthositic rocks occurring at certain levels in the layered rocks at Kûngnât and Grønnedal-Íka.

A more complex situation is illustrated in fig. 3, a semi-diagrammatic representation of a kakortokite where a multi-component cumulus has been deposited a) under tranquil conditions, (lower portion) and b) during flow sufficiently strong to retain much of the cumulus feldspar in suspension, thus yielding a horizon relatively enriched in the heavier cumulus minerals, at the same time ensuring good lamination of that fraction of the feldspars as was able to settle (upper portion). Cases where the cumulus consists only of tabular feldspars stand a better chance of being close packed than those where, for example, stout

Fig. 3. Semi-diagrammatic section across the base of a thin mafic horizon within the kakortokite series. The mafic rock is rich in arfvedsonite, ainigmatite, and eudialyte, and shows pronounced feldspar lamination in contrast to the underlying 'white kakortokite'.

prismatic crystals of olivine or nepheline are present to mechanically hinder the close parallelism of the feldspars. In some cases, e. g. in some of the Grønnedal foyaites and Narssaq gabbros, where there are intimations of very close packing (involving a high degree of lamination and frequent straining or fracturing of the feldspars where they have been bent around obstructing olivines, nephelines etc.), it is likely that a subsidiary factor was the load imposed on lower levels of the crystal mush by overlying material. This is a form of filter-pressing and the primary lamination due to flow orientation is enhanced by this imposed schistosity. This would only be effective when the depositional rate was particularly high compared with the rate of intercumulus crystallization and this is not thought to be the general case in the rocks under discussion.

Since there is no sharp discontinuity between cumulus mineral and material subsequently added to it, it is difficult to estimate how much of a single and moderately idiomorphic crystal has grown after settling, especially in those cases where strong normal zoning in the intercumulus portion is not developed. However, it is easy to arrive at a minimum figure for the volume of the intercumulus liquid by point-counting mineral phases believed to be exclusively intercumulus in origin. Although the present paper is based on purely qualitative considerations, since no serious attempt has yet been made to derive the relative amounts of cumulus and intercumulus in any of these south Greenland rocks, a useful guide is provided by the answers which have been deduced for the layered rocks of other intrusions. WAGER, BROWN and WADSWORTH concluded that at Skaergaard the loosely accumulated mush contained ca. 45 % of intercumulus and at Stillwater and Rhum respectively, HESS (1939) and BROWN (1956) arrived at a figure of ca. 50 % of intercumulus material.

The following table indicates the principal cumulus minerals in the five rock types.

	Gabbro	Anorthosite	Syenite	Foyaite	Kakortokite
Plagioclase (Labrad.)	×	×	..	..	..
H. T. Alk. Feldspar	..	..	×	×	×
Nepheline	..	..	..	×	×
Olivine	×	..	×	..	..
Clinopyroxene	..	..	×	×	..
Arfvedsonite and Ainigmatite	..	..	..	..	×
Fe-Ti oxide	×	..	×	..	×
Apatite	×	..	×	×	..
Eudialyte	..	..	..	..	×

N. V. USSING (1912), considered the possibility that the sodalite concentration in some of the nepheline syenites at Ilímaussaq (the naujaites), arose through flotation of early sodalites. The naujaites may represent the 'upper border group' (cf. WAGER and DEER 1939), of an intrusion in which the kakortokites represent the floor-accumulated layered series. If this were so, then the parent magma had, over much of its cooling history, a density intermediate between those of sodalite and nepheline at the temperature of their crystallization and the sodalite, although an early formed mineral, did not sink to join the floor cumulus. The analogy to an upper border group of Skaergaard type is not close since the naujaites may represent a form of flotation cumulate whereas cumulates of this type are quite absent at Skaergaard.

In the gabbros, strongly zoned intercumulus plagioclase passes fairly abruptly into micro- or cryptoperthitic alkali feldspar which represents part of the ultimate trapped liquid. The alkali feldspar occurs as small turbid angular areas of which that figured in plate 1 fig. 2 is a typical example. Much of the albite found interstitially or mantling the earlier cryptoperthitic or antiperthitic feldspars in the syenitic rocks may well represent late crystallization of sodic intercumulus liquid. Such albite probably did not originate through unmixing of homogenous feldspar and may be distinguished as 'extra-perthitic' albite (see fig. 14).

In the gabbros and anorthosites, pyroxene occurs only in the intercumulus in contrast to the syenites of Kûngnât and Grønnedal where pyroxene was evidently a cumulus mineral throughout substantial thicknesses of the layered rock series. In these syenitic rocks, 'normal' zoning of the intercumulus pyroxenes around the virtually unzoned cumulus portions is characteristically present giving successively more Na- and Fe-rich zones.

In the Kûngnât syenites, the oxidation state was sufficiently low for iron-rich olivines to join the cumulus during most of the time required for the accumulation of the observable layered series. The accompanying pyroxene ranged from augite through ferroaugite and ferrohedenbergite to aegirine-augite, according to the level within a particular layered sequence. In the Grønnedal nepheline syenites which presumably precipitated from a more highly oxidised magma, olivine crystallization was probably inhibited early on and precipitation of aegirine-augite was primarily responsible for the removal of iron (and magnesium) from the melt. In the still more sodic and highly oxidised melts from which the kakortokites were derived, arfvedsonite together with some ainigmatite became a primary ferromagnesian phase. At times early-grown aegirine crystals were also involved in tke kakortokite cumulus. Intercumulus fluorite occurs in each of the syenites. Similarly carbonates precipitated late occur within the Kûngnât and Grønnedal syenites, joined by cancrinite in the latter. Surplus chlorine precipitated as sodalite from the intercumulus liquid of the kakortokites.

Since fractionation in the large and slowly cooling magma chambers must itself have been a very slow process, it is likely that zoning due to fall of temperature in the cumulus minerals was only slight and that significant zoning did not commence until after the crystals had come to rest. However, in the gabbros, oscillatory zoning is commonly present in the cumulus plagioclase. This fine scale multiple zoning appears to involve a compositional variation of ca. 3–4 $^0/_0$ An and is of quite different character from the normal zoning of the intercumulate plagioclase. Carr (1954) considered that oscillatory zoning in primary plagioclase of the Skaergaard layered series resulted whenever the early crystals were carried in suspension through several cycles of the convective circulation; each abrupt change in the zoning reflected the drop in hydrostatic pressure when the crystals were borne to higher levels in the magma. In the present instance, the oscillating zones are probably causally connected with vapour pressure variation during crystal growth (associated with volcanic activity above) rather than with growth at different hydrostatic levels.

In a layered series formed by gravitational settling of early mineral phases in a magma where crystal seeding is predominantly near the roof, the resulting cumulus minerals of any particular species and at any one level in the series should show an overall uniformity in size. Tolerable uniformity is displayed within the various syenites and is also seen in the gabbros at those localities where lamination is pronounced. At several of the layered 'centres' along the gabbro dykes, sharply defined mafic bands are developed, and in these rocks the cumulus minerals, in particular the olivines, show a considerable range in grain size. In these localities the vigorous banding may well be a reflection of abrupt vapour pressure changes within the magma chamber, this inducing rapid nucleation of one or more primary precipitate minerals at all levels within the chamber. The anorthosites especially are characterised by the disparity in sizes of the constituent labradorites, and it is tentatively proposed that these were precipitated from a basic magma, closely related to the parent magma of the gabbros, in which primary plagioclase was able to seed at all levels; in other words, the eventual size of any single crystal was principally determined by the distance through which the growing crystal settled.

TYPES OF CUMULATE

Wager et al. (1960), suggest the name 'orthocumulate' for rock consisting of "cumulus minerals together with the products of crystallization of the intercumulus liquid which necessarily has the composition of the contemporary magma". Where intercumulate growth on to the cumulus minerals continued by diffusion of material from the overlying magma, the 'normal' zoning characteristic of orthocumulates may be lacking. Cumulates of this sort, i. e. those where the intercumulate material has been modified by diffusion and is no longer identical compositionally with the contemporary magma, have been termed 'adcumulates'.

It is explained by these authors that the adcumulus process, which gradually reduces the intercumulus liquid by mechanically pushing it out, may sometimes reduce the amount to vanishing point. Thus the extreme case of an adcumulate shows no material representing trapped remnants of interstitial magma. 'Mesocumulates' are those rocks in the condition intermediate between the extremes represented by ideal orthocumulates and adcumulates and is the class into which fall the cumulates under discussion. Most are probably not far from the ideal orthocumulate state although the anorthosites and some of the nearly monomineralic perthositic rocks from Kûngnât and Grønnedal may more closely approach the adcumulate condition.

THE NARSSAQ-TUGTUTÔQ GABBROS

Olivine gabbro, commonly troctolitic, outcrops to the west of the main Ilímaussaq intrusion as broad dykes of up to 700 m. wide. These can be traced westwards for some fifty kilometres into the Davis Straits. These rocks are inferred to be derivatives of an alkali olivine basalt magma. Whereas these dykes are, over much of their course, composed of massive and structureless gabbro, certain sectors possess a synformal

Fig. 4. A diagrammatic vertical section through the unmodified cumulus of a Tugtutôq gabbro deposited during gentle flow conditions. The cumulus is composed principally of plagioclase, olivine and ore.

structure as indicated either by banding or by the feldspar orientation or by both of these features. The maximum dip of the structural elements within these layered 'cells' does not normally exceed 45°, except in the marginal zones where, on occasion, steep angled 'fluxion banding' has been developed. Approximately a dozen more or less independent 'cells' have now been recognised within the gabbros. Although these have much in common, they have sufficient individuality for it to be reasonable

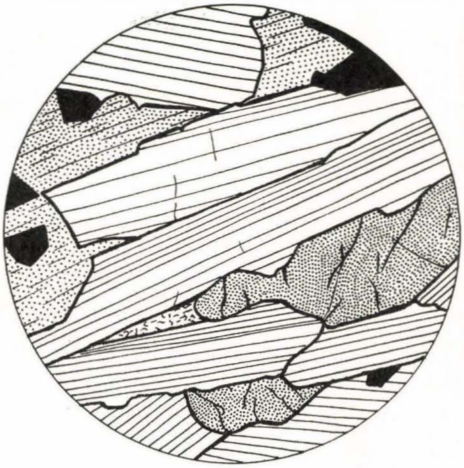

Fig. 5. A thin section of a Tugtutôq gabbro representing the type believed to have resulted from the crystallization of a laminated cumulus mush of the sort illustrated in fig. 4. The field contains plagioclase, olivine (close stipple), augite (open stipple), ore and a small angular area of alkali feldspar interstitial between two plagioclase tablets and an olivine crystal. × 15.

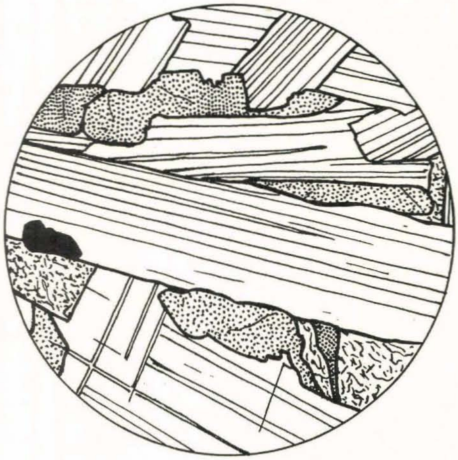

Fig. 6. Thin section of an olivine gabbro of the same type as illustrated in fig. 5. Here the apatite (stippled), is mainly of intercumulus origin and occurs interstitially and even sub-ophitically. Some turbid interstitial alkali feldspar is also shown. × 15.

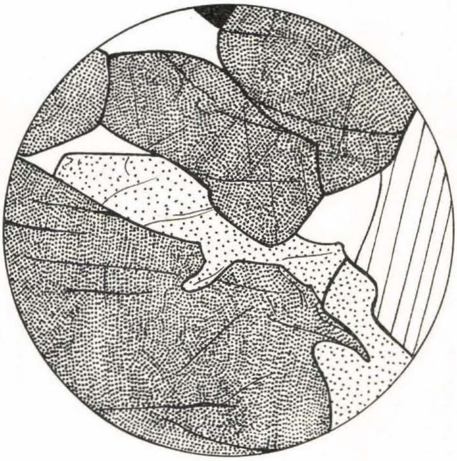

Fig. 7. A further thin section of olivine gabbro of the same type as shown in figs. 5 and 6. The crystal outlines of the apatite (open stipple) and olivine (close stipple) have been substantially modified by intercumulus growth. × 15.

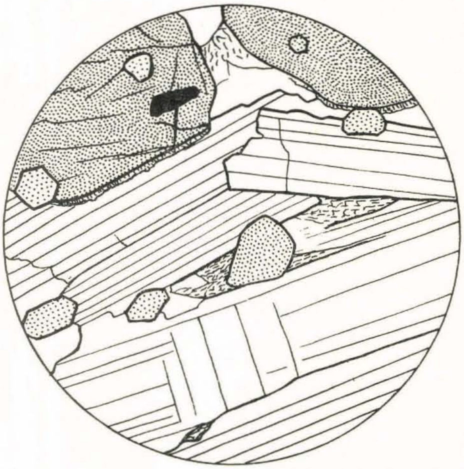

Fig. 8. A laminated gabbro from Tugtutôq in which the early apatites (open stipple) and olivines (close stipple) have been only slightly modified by intercumulus growth. Turbid areas of alkali feldspar occur in interstitial spaces. × 15.

to suppose that the circumstances of crystallization differed considerably in different parts of the gabbro body. In three areas, feldspar lamination is developed to a high degree. At two of these, the feldspar lamination defines synformal structures within the dykes and at the third locality, namely the peninsula north of Narssaq village, so little of the gabbros appear above sea level that it is only by inference and analogy that the layered and laminated gabbros are considered to represent a small portion of a formerly extensive synformal structure. In this latter area, such mafic bands or schlieren as are present are ascribed to crystal

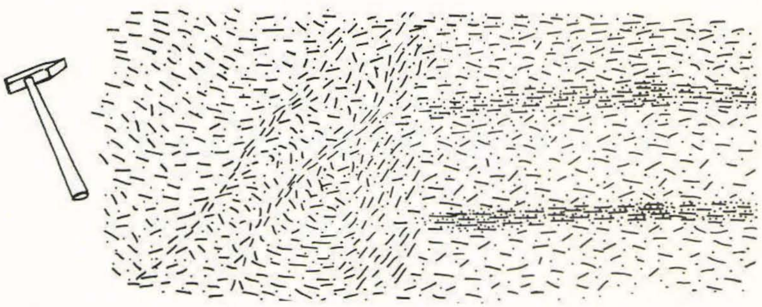

Fig. 9. Two thin mafic horizons within the Narssaq gabbros interrupted by a zone of disturbance. The disturbance is believed to have been due to movement (faulting) of the semi-consolidated crystal mush. Feldspar parallelism is present within the mafic layers but not in the accompanying average gabbro.

winnowing by magma flow. Fig. 4 illustrates schematically the cumulus of a laminated gabbro from Tugtutôq. The actual rock upon which fig. 4 is based consists of 50.3 % plagioclase, 29.4 % olivine, 14.5 % ore, 1.3 % apatite, 3.7 % of alkali feldspar and biotite and 0.8 % pyroxene.

The mafic lenses and horizons in the layered gabbros are rich in idiomorphic olivine (hyalosiderite), ilmenomagnetite and apatite, and these three minerals, together with calcic labradorite, are believed to have precipitated together as cumulus minerals from the contemporary magma. Augite, biotite and micro- (or crypto-) perthite occur interstitially and are considered to be exclusively intercumulus products. The growth period of the ore was extensive and in many of the layered rocks a high proportion of the ore must have grown from the intercumulus liquid. In one specimen from a fairly typical mafic horizon near Narssaq, representing a gravity concentrate of heavy cumulus minerals, the modal composition was 6.6 % plagioclase, 51.6 % olivine, 27.7 % ore, 7.4 % apatite, 1.2 % pyroxene and 5.5 % biotite. An interesting feature is that in some of the concentrates of olivine, ore and apatite, from which primary plagioclase had been efficiently sifted, there is an unusually high proportion of augite, biotite and alkali feldspar and strongly zoned plagioclase (andesine). This suggests that packing could be very loose in these 'heavy concentrates'. On the other hand, in some of the almost monomineralic labradorite-rich facies where there is high parallelism of the tabular crystals and close packing, the subordinate quantities of augite, cryptoperthite, ore, and late apatite, assumed the form of extremely thin interstitial wedges.

Convincing evidence that the rather poorly defined mafic bands in the Narssaq region are the result of current sorting is that whereas the intervening average rock may show a notable absence of any preferred crystal orientation, the relatively few early feldspar laths within the mafic horizons are orientated parallel to the layering (fig. 9). The inference is that the average rock accumulated in still conditions and that the mafic lenses and bands were due to current winnowing. An analogous restriction of lamination to mafic horizons has recently been described for the layered granites at Tigssaluk, to the north of Kûngnât, (Harry and Emeleus 1960).

THE ANORTHOSITES

Masses of anorthositic rock ranging in size from one great block of over 100 m. across to single fractured pieces of labradorite crystals occur within the gabbros at many localities. The large masses enveloped by the gabbros on the Assorutit peninsula of Tugtutôq themselves show a crude banding which results from the alternation of layers of well-laminated feldspar rock with slightly more mafic horizons of more disorientated material.

Since the anorthosites appear to be detached and rootless within the gabbro, the generally low angle of dip of the layering is probably fortuitous. The absence of rhythmic gradational layering precludes the means of telling whether the blocks have been structurally inverted. Mineralogically the anorthosites are very similar to the gabbros, and it may be reasonably assumed that they formed from a similar parental liquid. On this ground it is considered that the feldspar concentration resulted from plagioclase settling rather than by flotation. There is a thickness of at least 30 m. of layered anorthosite and it is most improbable that such a pile resulted from current sorting of the 'normal' primary precipitate assemblage of the gabbros. Brown (1956, p. 47) refers to the experimental work of Yoder on the system An-Fo-water in his discussion of the origin of the layered allivalite-peridotite sequence on the Isle of Rhum. With decrease of water vapour pressure, the Fo-An eutectic is raised and shifted towards the Fo side of the diagram, thus extending the anorthite field. Since the Tugtutôq anorthosites are essentially plagioclase-olivine rocks with the olivine subordinate and entirely of intercumulus origin, it is not unlikely that they were formed by the crystallization of a liquid (approximating to a plagioclase-olivine

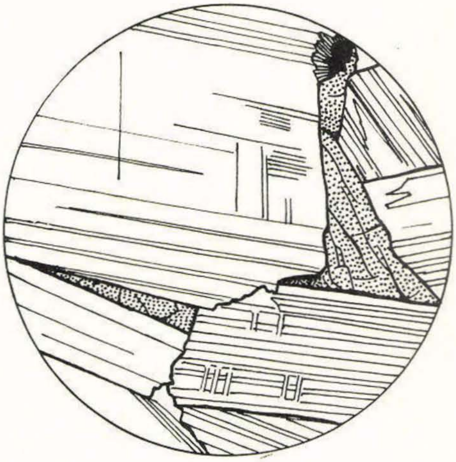

Fig. 10. Interstitial and sub-ophitic olivine occurring within a laminated anorthosite from Tugtutôq. A small ore grain with a biotite reaction rim is seen in the lower upper part of the field. × 10.

melt) which after a significant fall in vapour pressure was precipitating labradorite alone. By continued fractionation within the intercumulus liquid and with the depletion of the melt in the plagioclase component a stage was reached, analogous to the Fo-An eutectic, at which feldspar and olivine were precipitating together. In reality such a stage was probably more closely comparable to the anorthite-forsterite cotectic in the An-Fo-Di system investigated by Osborn and Tait (1952). A small percentage of augite, biotite, and alkali feldspar occur interstitially in the anorthosites. A little ore and apatite is also found and these two minerals may conceivably have been accessories in the cumulus. The frequent absence of any strong intercumulus zoning near the edges of the labradorite crystals suggests that these rocks have affinity to the adcumulitic rocks of Stillwater (Hess 1939) and Rhum (Brown 1956).

The anorthosites are thus believed to have formed as accumulative rock from magma which was temporarily precipitating labradorite alone. Since the feldspar is a rather sodic labradorite, averaging An_{57}, it is likely that the contemporary magma was dioritic in composition, rather than basaltic. The wide range in crystal size of these feldspars is taken to indicate that seeding was occurring at all levels in the magma, as explained above. Periodic current activity within the magma was sufficient to orientate the settling feldspars, but was not sufficient to effect any observable sorting according to size. Periods of tranquillity allowed poorly-packed, unlaminated horizons to form, these being relatively more mafic by virtue of their greater content of intercumulate olivine.

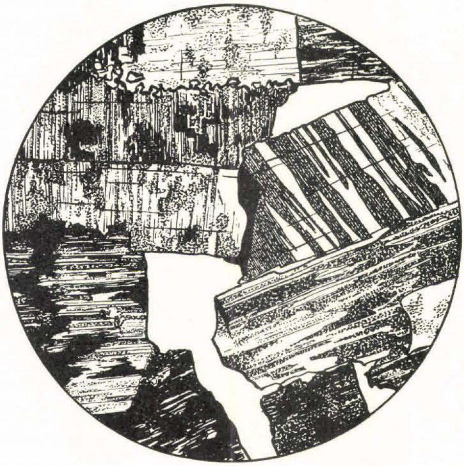

Fig. 11. Thin section of a quartz syenite from Kûngnât. The field shows cumulus alkali feldspars modified by intercumulus growth, together with quartz entirely of intercumulus origin. Crossed nicols. × 20.

THE KÛNGNÂT SYENITES

The western syenite stock in the Kûngnât alkaline complex (Upton, 1960) is stratiform and displays both rhythmic banding and igneous lamination. These syenites have been divided into an upper and a lower layered series, each of which shows some cryptic variation. The intrusion is important in demonstrating that such processes as fractional crystallization resulting from crystal settling in a convecting magma body can, on occasion, be as influential in the development of variation in an alkaline rock series as in the production of some layered basic intrusions.

In several respects the conditions under which the western Kûngnât syenites formed were intermediate between those of the gabbros described above and of the Grønnedal nepheline syenites. In contrast to the latter, the Kûngnât syenites would appear to have formed from a magma which remained in a relatively reduced state for the greater part of its cooling history. During this time the cumulus minerals included iron-rich olivine (ferrohortonolite→fayalite), a high temperature Fe-Ti oxide (which in the earlier cumulates gave the ferrous-orthotitanate, ulvöspinel, as an exsolution product) and pyroxenes mainly in the range ferroaugite-ferrohedenbergite, i. e. the iron was removed from solution predominantly in the ferrous condition. Nevertheless, it is inferred from the fairly high intercumulate amounts of Na. Fe.''' amphibole and lepidomelane that

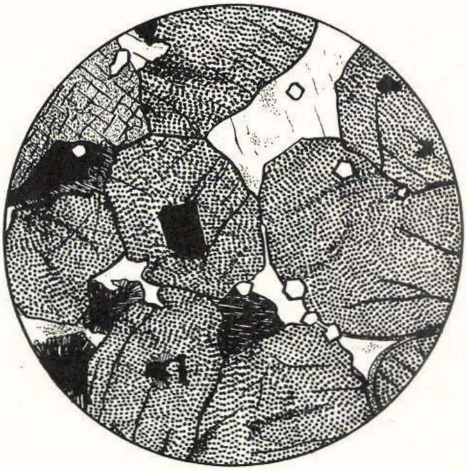

Fig. 12. An olivine and pyroxene cumulate within the Kûngnât syenites. The idiomorphic ferrohortonolite crystals (heavy stipple) represent scarcely modified cumulus crystals whereas the feldspar is virtually all of intercumulus origin. Also shown are cumulus apatites, ore grains and one crystal of ferroaugite (top left), together with biotite reaction rims around the ore and occasional thin rims of alkaline amphibole around the olivines. × 20.

the fractionating magma was, from the earliest stages, more highly oxidised and more water-rich than the basic magma that yielded the gabbros. In the Kûngnât and Grønnedal syenites and in the Tugtutôq-Narssaq gabbros, the phosphorus contents of the fractionating magmas was high enough during much of the time to permit primary crystallization of apatite, in each case this becoming concentrated in the mafic segregates. In the case of the magma yielding the Tugtutôq gabbros, calcium was mainly subtracted by precipitation of basic plagioclase and was removed from the residual liquids by growth of intercumulus augite and by the continued growth of the plagioclase. In contrast, at Kûngnât, relatively calcic clinopyroxene precipitated alongside the Ca-poor alkali feldspar ($An_{11} \rightarrow An_4$) as a cumulus mineral throughout much of the cooling history.

Rhythmic layering in the Kûngnât syenites has been explained in terms of gravitational sorting of cumulus crystals by relatively fast moving currents. Laminated, but unbanded syenites at other levels are thought to have been produced by settling through gently moving magma and the unlaminated-unbanded syenites probably represent precipitation in a quiescent magma. Feldspar lineation, which may well be present in the laminated and banded rocks, was not observed in the field. Crystal form of the feldspars is best preserved in the well-laminated rocks, this possibly being a consequence of closer packing and more limited intercumulus growth.

Fig. 13. Thin section of a specimen from a mafic horizon in the upper layered series of syenites from western Kûngnât. The field shows cumulus alkali feldspars and fayalite each of which has been significantly modified by intercumulus growth while still retaining an idiomorphic habit. A small area of intercumulus ore is shown. × 30.

On the basis of the very clear evidence for strong magmatic flow being a vital factor in the development of mafic horizons in the layered Kûngnât and Nunarssuit syenite assemblages, (see T. C. R. Pulvertaft, G. G. U. report 1958) the occasional olivine-clinopyroxene-rich schlieren present in some of the other south Greenland quartz syenites may also be products of current winnowing on a mixture of cumulus minerals.

NEPHELINE SYENITES IN THE GRØNNEDAL-ÍKA COMPLEX

The Grønnedal-Íka nepheline syenite and carbonatite complex, lying to the east of Ivigtut, was first described by Karen Callisen (1943), who gave a fairly detailed account of the foyaitic and pulaskitic components. The area is at present the subject of an intensive reinvestigation by Dr. C. H. EMELEUS, who mapped the complex for the Greenland Geological Survey.

At Grønnedal the basement gneisses have been intruded by an early group of nepheline syenites which were later cut by a central body of carbonatite. The alkaline complex was subsequently intruded by a number of thick olivine dolerite dykes and numerous smaller trachytic dykes. Finally, the whole was subjected to severe transcurrent faulting in two directions, the period of faulting overlapping the later phase of dyke intrusion. The main body of nepheline syenites suffered much alteration as a result of the later intrusions and dislocations. Nevertheless, in the north-west of the complex it is possible to distinguish several different stages in its emplacement and consolidation. Two major series of laminated nepheline syenites are enclosed by a thin marginal zone of medium grained, granular nepheline syenite. One series, structurally the lower, contains medium to coarse grained nepheline syenite consisting of alkali feldspar, nepheline, clinopyroxene, cancrinite, biotite, and lesser amounts of carbonate, fluorite, zircon and ore. This group is characterised by the thinness of the feldspars which often show an extreme lamination or trachytoid texture. Conformably overlying this lower series is a sheet of gneiss and above this lie the coarser-grained syenites that comprise the bulk of the complex. This higher series is mineralogically similar to the lower but possesses thicker feldspar tablets and occasionally contains pronounced mineral layering. This latter takes the form of thin bands rich in aegirine-augite, apatite and amphibole. The banding and lamination of this upper layered series is also conformable to the underlying syenites and the intervening horizon of gneiss.

When allowance is made for distortions due to dyke intrusion and transurrent faulting, the original form of the intrusion is seen to be nearly circular or slightly elongate in a N.W.-S.E. direction and within this, the layering of the rocks is directed centrally.

Interest centres chiefly on the relatively undisturbed north-western part of the complex and here the disposition and texture of the rock types is such as to suggest, by analogy with other intrusions where evidence is more forthcoming, that one is dealing with a suite of rocks evolved by bottom-accumulation of early mineral phases within an early-formed 'border group'. CALLISEN considered that gravitative differentiation was a significant factor at Grønnedal and, on the assumption that this suite of laminated syenites does in fact represent an alkaline cumulate, the cumulus must have consisted principally of feldspar (sanidine) and nepheline, with apatite and aegirine-augite important at some stages. Magnetite and zircon may have made a minor contribution. The aegirine-augite continued its growth to a late stage, the crystals becoming more sodic toward their marginal zones; the crystals are generally anhedral. In the lower laminated sequence it is possible that all the aegirine-augite grew from intercumulate liquid trapped within the feldspar-nepheline cumulus. In the sequence above the gneiss raft, however, the crystal form of the pyroxenes and their concentration into schlieren and bands, strongly suggests that here at least they formed a part of the cumulus (fig. 15). The cancrinite, carbonate (sideritic),

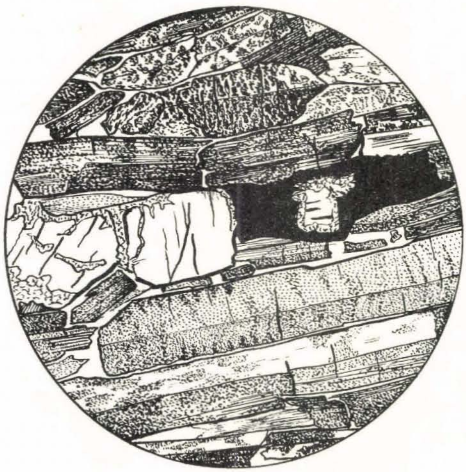

Fig. 14. A section of a laminated feldspar and nepheline cumulate occurring within the Grønnedal-Íka layered syenites. This is an example of a very close packed cumulate (cf. fig. 10) in which intercumulus addition to the feldspars and nephelines has been minimal. The occasional fracturing and bending of the feldspars suggests compaction under load. The three nepheline crystals shown have each suffered some alteration to cancrinite. Minerals entirely of intercumulus origin include biotite (upper part of field), magnetite (centre) and albite which surrounds the euhedral cumulus feldspars. × 15.

and fluorite, are believed to be derived solely from intercumulus crystallization.

Among the layered syenites in the north-western area there are two varieties, differing in texture and colour although very similar in mineralogy. One variety is of a pale lilac-grey colour and is normally well laminated. The other variant is duller, brownish and less obviously fresh than the lilac-grey rock and tends to contain a more randomly-oriented assemblage of feldspar, not infrequently arranged in complex swirl-patterns reminiscent of those seen in the gabbros north of Narssaq. These two types occur as horizons in the succession below the gneiss raft, grading imperceptibly into one another: each wedges out laterally to give way to the complimentary rock type although individual layers may have a quite considerable areal extent and may, to some degree, be mapped out individually. In the layered syenites above the gneiss sheet it is less easy to distinguish the two variants although both are still present.

The difference in colour and texture within the lower series might also be correlated with the presence or absence of magmatic currents during their deposition, the cumulus minerals of the 'lilac syenites' being

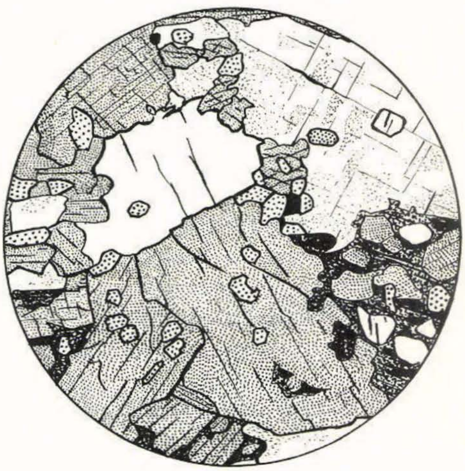

Fig. 15. Section of a mafic syenite from a horizon in the Grønnedal-Íka nepheline-syenites. The cumulus minerals include aegirine-augite (close stipple), apatite (coarse stipple), alkali feldspar (slightly turbid) and nepheline (clear). Substantial intercumulus growth of these minerals has resulted in their becoming nearly anhedral. Interstitial and poikilitic biotite, believed to be solely of intercumulus origin, is also present. × 20.

deposited during conditions of gentle magmatic flow which oriented the crystals and imposed a closer packing than would have occurred had the crystals taken up a more nearly random orientation on the chamber floor. On the other hand, the brownish syenites, often very poorly laminated, may represent cumulus minerals deposited under quieter conditions. The difference in their colour is mainly the result of the abundance of alteration products in the dull brown variety, the lilac-grey rock being composed of much fresher minerals, particularly the nepheline and pyroxene. The excessive alteration of the brown syenites, and especially of the unlaminated horizons, may be a consequence of their containing a higher percentage of intermulus liquid than was the case with the better packed lilac-grey rocks. In the former, fractionation of the abundant intercumulus liquid produced a CO_2-H_2O rich residue which hydrothermally altered the neighbouring crystals.

A factor that may have aided in the retention of a higher proportion of residual liquid is that the slightly higher proportion of nepheline in the brownish syenites may have prevented close packing of the feldspars. Some hydrothermal alteration around 'pore material' may be a characteristic of orthocumulate rocks just as is strong 'normal' zoning of the intercumulus minerals. The depositional rate may have been too high to allow significant intercumulus modification by the adcumulus process. With the difference that these rocks appear to be almost ideal orthocumulates whereas the Tugtutôq anorthosites have adcumulate tendencies, the alternation of laminated and unlaminated horizons appears to be directly comparable in the two instances. In these syenites, as in the anorthosites, the inferred magmatic currents would seem to have produced no obvious mineral sorting.

At certain levels in the Grønnedal sequence, layered rocks appear in which aegirine-augite is lacking and in extreme cases the rock is virtually a perthosite. This may have been the result of changes in water vapour pressure which deflected the system temporarily from cotectic crystallization, or the result of thorough gravity sorting of the cumulus by magma currents. Such rocks are characterised by excellent lamination and they are finer grained than is usual in the upper group. In these, feldspar and nepheline alone are thought to have built up the cumulus (fig. 14). Phases appearing in the intercumulus are albite, biotite, cancrinite and ore. The complimentary rock type may well be the mafic horizons within the foyaites, referred to above, in which considerable quantities of apatite and aegirine-augite must have been present in the cumulus.

THE KAKORTOKITES

The southern sector of the Ilímaussaq nepheline syenite intrusion comprises a layered sequence of foyaitic rocks peculiarly rich in eudialyte. These rocks were named kakortokites by Ussing (1912) who was the first to describe them in detail. The sequence displays a remarkable large scale banding which is essentially due to thick units of feldspathic rock alternating with horizons of arfvedsonite-rich rock. Ussing proposed (op. cit., p. 360) that repeated changes in vapour pressure within the parent 'agpaitic' magma may have been primarily responsible for the major banding. Ussing was reminded of Harker's accounts of the layered ultrabasic rocks on the island of Rhum. These latter have themselves been explained as a bottom accumulate formed in a magma chamber beneath a volcano; the magma undergoing changes in partial pressure of dissolved water, as a result of periodic volcanic activity (Brown 1956). However, small scale layering features within the kakortokites (analogous to those within the Rhum layered series) suggest that here, too, magma currents played some part in the depositional history. Small scale gravity-stratified and often impersistent layers, disconformities within the minor layering and incipient trough banding are frequently observed. Just as in the gabbros of the Narssaq region where preferred orientation of the feldspars is most pronounced

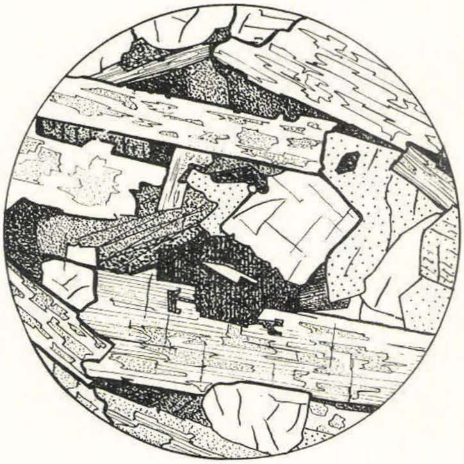

Fig. 16. Section of moderately laminated 'white kakortokite' from the southern part of the Ilímaussaq complex. The major cumulus minerals in this rock are alkali feldspar (now microcline antiperthite), and nepheline, (cf. fig. 14). The eudialyte (open stipple) and arfvedsonite-aegirine areas (both minerals shown in close stipple) are, in this particular specimen, believed to be mainly of intercumulus origin. × 10.

in mafic layers, so here again it is common for the feldspars within the basal parts of mafic bands to lie parallel and to lie more randomly in the leucocratic rock immediately underlying the base of a mafic layer, (fig. 3). This feature has already been commented upon in the introduction.

In a broad way the kakortokites resemble the layered nepheline syenites in the north-west of the Grønnedal-Íka intrusion. In both cases, a suite of coarse-grained 'foyaitic' rocks dip gently inwards from the cooling wall. In both cases, it appears that the dominant cumulus mineral was alkali feldspar (probably sanidine, now seen as microcline-microperthite), with subordinate nepheline. Whereas zircon was an almost insignificant component of the Grønnedal series, eudialyte was an important cumulus mineral in the kakortokites. Possibly a prolonged supersaturation with regard to zirconium in the evolving 'agpaite' magma was eventually relieved by large scale precipitation of eudialyte during the naujaite-kakortokite phase. Conversely, whilst phosphorus concentration at Grønnedal was sufficient for apatite to appear as a minor cumulus mineral, subtraction of phosphorus had presumably reached an advanced grade at Ilímaussaq at the time of kakortokite formation and cumulus apatite is not found.

Sodalite, analcite and albite appear to be exclusively of intercumulus origin. Where the feldspathic layers are disordered, the thickness of the idiomorphic feldspar tablets is often conspicuously greater than in associated mafic horizons showing close parallelism of the arfvedsonites and feldspars. This may be a reflection of more uninhibited feldspar growth in the loosely packed cumulus than in the laminated mafic horizons where closer packing prevailed.

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Plate I.

Fig. 1. Portions of two almost euhedral alkali feldspars separated by interstitial hornblende, seen in a thin section of a laminated syenite from the lower layered series of western Kûngnât. In such rocks it is suggested that, as a result of moderately close packing of the cumulus, intercumulus enlargement of the feldspars was arrested at an early stage and the euhedral outlines often preserved. Furthermore, it is probable that practically all the feldspar growth was complete before the onset of exsolution. The two feldspar crystals are seen in approximately (100) section (upper crystal) and (001) section (lower crystal). The hornblende is entirely a product of intercumulus crystallization. Crossed nicols. × 20.

Fig. 2. A typical interstitial area consisting of alkali feldspar and its alteration products, present in a laminated gabbro from Tugtutôq. Such material probably represents the crystallization of the ultimate fractionate of the interprecipitate liquid trapped between the growing plagioclase crystals. The plagioclase crystals display pronounced normal zoning of their outer (intercumulus) portions around such areas. In this illustration this zoning is only apparent in the lowermost of the three crystals. Crossed nicols. × 20.

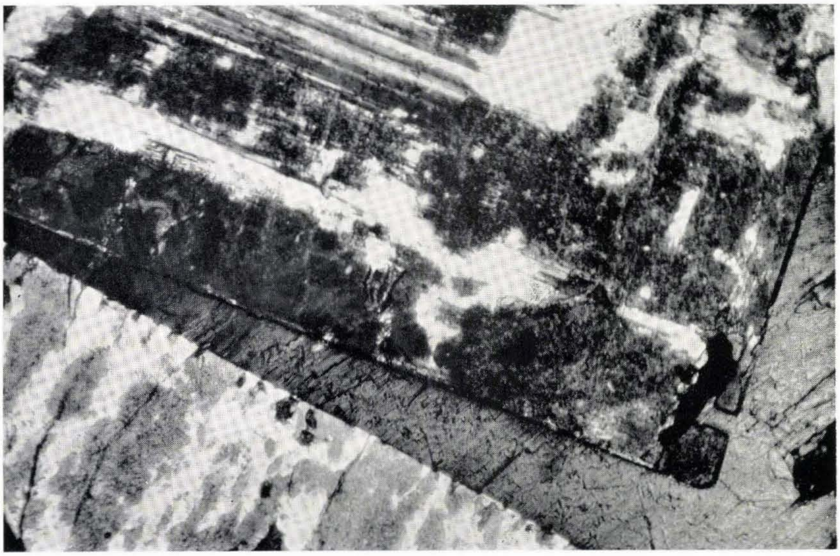

Fig. 1

Fig. 2