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CONTRASTED STYLES OF IGNEOUS LAYERING IN THE GARDAR PROVINCE OF SOUTH GREENLAND

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ABSTRACT

Igneous layering is developed in nearly all the larger Gardar intrusions of south Greenland in rocks varying from gabbro to granite in composition. The syenites, which are the most abundant rocks in these intrusions, display the finest examples of layering. Layering comprising olivine-rich bands in more feldspathic gabbro forms synclinal structures in the large (over 200 m thick) gabbro dikes.

Layering is pronounced in the pyroxene-fayalite syenites of Kûngnât and Nunarssuit. Cumulus clinopyroxene and fayalite have been concentrated in layers as a result of gravity sorting under the influence of currents. In the petrographically similar syenite of the Klokken intrusion large-scale mafic banding and concordant lamination form an almost perfect saucer-shaped structure.

Most of the syenites of the Ilímaussaq Intrusion show banding, but the agpaitic rocks are the most striking. The kakortokites are laminated bottom accumulates with color banding due to rhythmic repetition of black, red and white bands corresponding to arfvedsonite/aegirine, eudialyte and feldspar concentrations respectively. Complementary banding occurs in the naujaite which formed simultaneously as a flotation cumulate. The residual magma crystallized to form the highly fissile lujavrites, which are locally banded as a result of alternating formation of aegirine and arfvedsonite. Fluctuations in pressure are thought to have caused the banding in the agpaites.

The nepheline syenites of the Grønnedal-Ika complex are characterized by pronounced feldspar lamination, locally accompanied by mineral layering.

Mineral layering is locally conspicuous in the Helene Granite where mafic minerals (including fayalite and clinopyroxene) are concentrated into layers as a result of gravity sorting assisted by magmatic currents.

INTRODUCTION

Poldervaart and Taubeneck (1960) commented that well-layered plutons are relatively uncommon, and that most information concerning layered intrusions has come from mafic bodies. These wholly reasonable remarks serve to emphasize the great interest of south Greenland to students of igneous geology. Igneous layering is developed in nearly all the larger Gardar intrusions in the area and in rocks ranging from gabbro to granite in composition. It is in the syenites, however, that the finest examples of layering are seen.

Detailed mapping of the Gardar intrusions was begun by the Geological Survey of Greenland in 1955 and has not yet been completed. This paper is a review of what is known at present concerning layering in these intrusions, special emphasis being placed on the Ilímaussaq and Nunarssuit syenites with which the respective authors are most familiar through their own investigations. It is being presented now in order to use the opportunity provided by the Symposium to draw world-wide attention to the remarkable wealth of layered features displayed in the Gardar province, even though much detailed laboratory work remains to be done.

THE GARDAR PROVINCE

General. Wegmann (1938) established that the Precambrian rocks of south Greenland belonged to two main cycles, which he termed Ketilidian and Gardar. The earlier Ketilidian cycle was one of sedimentation and tectogenesis. The Gardar period was dominated by igneous activity: it was initiated by the deposition of continental sandstones intercalated with lavas. These strata, despite their age more or less horizontal, rest with marked unconformity on Ketilidian basement migmatites in a down-faulted zone north of Julianehåb. Over a much wider area of south Greenland, between latitudes 60 and 62 north, numerous dike swarms, predominantly of basic composition, cut the basement. The intrusive centers, comprising mostly alkali rocks, are confined to the Ivigtut-Julianehåb area: generally speaking, with the exception of the Grønnedal and Igaliko complexes, these cut the dike swarms and are therefore late Gardar in age.

Faulting was widespread during the Gardar period. The most important faults are those running approximately east-west. These are partly responsible for the present distribution of the sandstones and lavas and are believed to have influenced the location of the intrusive centers.

Gardar intrusive centers. In order that the setting in which the layered rocks occur should be better understood, a brief summary of the Gardar intrusions and their salient features is given, in order from west to east (Fig. 1).

The *Kûngnât Complex* (Upton, 1960) consists of three pyroxene-fayalite syenite bodies which were intruded successively in order of increasing basicity with progressive easterly shift of center. Later an alkali gabbro ring-dike almost surrounding the syenites was emplaced. The complex is 5.4 km long by 3.2 km wide.

The *Grønnedal-Ika Complex* (Emeleus, in press) was, prior to faulting, an oval intrusion about 6 km long. It comprises nepheline syenites, commonly foyaitic in texture, and later carbonatite.

The *Nunarssuit Complex* (Harry and Pulvertaft, 1963) is a very large massif, at least 45 km long by 25 km wide, dominated by two pyroxene-fayalite syenite bodies, the Nunarssuit and Kitsigsut syenites, and the Helene Granite which has much in common with the Scandinavian rapakivis. Other members of the complex are gabbro, biotite granite and soda-granite.

The *Puklen Intrusion* (Pulvertaft, 1961), situated in Nunarssuit, is probably co-magmatic with the Nunarssuit Complex, being made up of pyroxene-fayalite syenite, quartz syenite and soda-granite. It is of the same order of size as the Kûngnât, Grønnedal-Ika and Tugtutôq central complexes.

The *Central Complex of Tugtutôq* (Upton, 1962) comprises some half-dozen ring-intrusions of related syenites and granites followed by a stock of perthosite syenite.

The *Narssaq Intrusion* lies just west of the Ilímaussaq Intrusion. The emplacement of quartz syenite and pyroxene syenite was followed by alkali granite.

The *Ilímaussaq Intrusion* (Ussing, 1911; Sørensen, 1958; Ferguson, in press) is famous for its remarkable development of per-alkaline syenites rich in chlorine and zirconium, expressed by the high content of sodalite and eudialyte respectively. Its evolution is outlined in a later section.

The *Igaliko Batholith* (Ussing, 1911; Ødum, 1927) is an enormous mass of nepheline syenites, with a marginal zone of augite syenite, on which work has only just commenced.

The *Klokken Intrusion* is a small oval mass of syenogabbro and augite syenite lying close beside the Igaliko Batholith.

The Gardar intrusions are amongst the best ex-

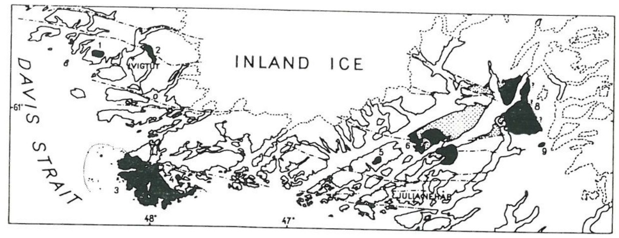

FIG. 1. Sketch map showing the position of the main Gardar igneous centers in south Greenland. 1) Kûngnât, 2) Grønnedal-Ika, 3) Nunarssuit, 4) Puklen, 5) Tugtutôq, 6) Narssaq, 7) Ilímaussaq, 8) Igaliko, 9) Klokken. The outcrop of the Gardar continental series is stippled.

posed in the world. The recent glaciation, during which erosion was very much more marked than deposition, and the harsh climate, which inhibits the growth of vegetation, are responsible for this. The strong relief in the area provides vertical sections up to 1700 m in some intrusions.

Giant Dikes. Some of the northeasterly Gardar dikes in south Greenland are of considerable thickness (up to a kilometer) and are referred to as giant dikes. The most noteworthy of these occur in Tugtutôq where, although predominantly gabbroic, they are composite, with the development of nepheline syenite or quartz syenite centers. Anorthosite xenoliths are a conspicuous feature of these dikes. Northeast of Nunarssuit similar if less persistent and somewhat thinner dikes have been mapped. In Nunarssuit the Eqaloqarfia dike, a 2–300 m thick basic dike, connects the Nunarssuit and Puklen intrusions, both of which cut off the dike.

IGNEOUS LAYERING

Gabbros. In the *Alángorssuaq Gabbro* of the Nunarssuit Complex (Harry and Pulvertaft, in press) banding and concordant lamination dip at moderate angles (between 30 and 50°) towards a deep focus in the center of the complex, now occupied by pyroxene-fayalite syenite and granite.

The mafic layers are usually between one and four cm thick, though some measure 30 cm in thickness. Generally they are between 5 and 30 cm apart. Within a single exposure most layers, considered individually, are of constant thickness. On a small scale also the banding is regular: well-defined "current-bedding," slumping and trough banding appear to be absent. Some of the broader layers are almost wholly composed of pyroxene. Local thin lenses of olivine-rock occur concordantly within the layering.

The lamination, which is usually highly pronounced, is due to the plane parallelism of tabular

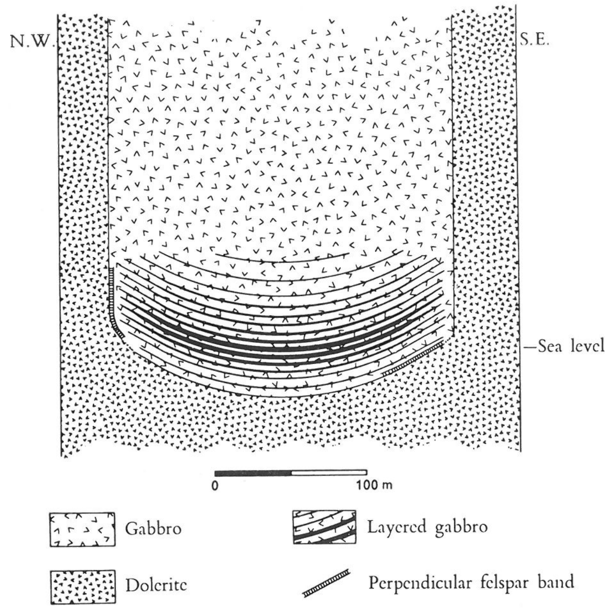

FIG. 2. Vertical section of the Eqaoloqarfia dike, drawn to scale. In the layered zone the olivine-rich bands are represented schematically.

plagioclase feldspars (commonly about 0.5 cm long) and elongate dark minerals. Within the plane of parallelism, however, the long axes of these minerals are haphazardly arranged.

Synformally disposed layered structures occur at intervals along the troctolitic gabbro *giant dikes* of Tugtutôq (Upton, 1961, 1962), although the northern dike is almost entirely massive. The layering may be displayed by banding due to difference in the relative amounts of plagioclase and dark minerals (principally olivine) or by the parallelism of the plagioclase crystals. In rare instances both banding and concordant lamination occur. Gravity stratification is rarely developed in the banding, which generally dips inwards from the dike walls at angles lower than 45° becoming horizontal in the axial region. However there are a number of localities where the internal structure is considerably more complex with, for example, two or more synforms occurring side by side.

In some places banding parallel to the cooling walls can be observed in these gabbros. Of particular interest are the vertical zones of "perpendicular feldspar rock" developed on the inner side of the normal fine-grained marginal facies of the northern gabbro dike in the western part of Tugtutôq. These zones are characterized by the possession of elongate curved plagioclase, standing perpendicular to the cooling wall, with the convex surface uppermost.

The layering in the *Eqaoloqarfia dike* defines a synform running parallel to the length of the dyke, with a maximum inward dip of the limbs of 36°. As shown in Fig. 2, the layering is developed in the lower part of a residuum of coarse gabbro in an otherwise normal dolerite dike. Homogeneous dolerite both underlies and forms a border zone to the gabbro. A perpendicular feldspar band, not more than 15 cm thick, occurs in some places at the border between the dolerite and gabbro: in this band the plagioclase feldspars have grown at steep angles to the margin of the dolerite.

The layering comprises bands rich in olivine set in ordinary coarse gabbro (feldspar tabulae 1–2 cm wide). Augite, the remaining important mineral, is interstitial to olivine and ophitic; it is not concentrated in the bands. The individual bands are regular and maintain a constant thickness over considerable distances. Passing up from the bottom of the layered succession the olivine-rich bands tend to become both thicker and more closely spaced until at about 15–20 m up they dominate over the intervening normal gabbro layers. Higher up the olivine-rich bands become thinner and more widely spaced, eventually dying out at about 50 m above the base of the gabbro, which shows no further layering in the exposed section of the dike (about 175 m high). All the rocks have been strongly uralitized, which impedes petrographic investigation.

Three further points must be taken into consideration when attempting an explanation of the layering:

1) No feldspar lamination has been observed in the dike, in spite of the favorable feldspar habit. 2) The bands do not show density grading; the top and bottom of the bands are equally sharply defined. 3) The olivines in some mafic bands are notably larger than those in the gabbro, reaching a centimeter or more in length.

The layering must have developed under tranquil conditions. The crystallization of the dolerite was followed by a period of quiescence and slight supercooling during which plagioclase feldspar grew from the margin of the dolerite into the residual magma. The onset of crystallization in the residuum was controlled by as yet unexplained cyclic changes which resulted in periods favorable to the crystallization and accumulation of olivine. With the cessation of these cyclic processes the remainder of the magma crystallized as normal gabbro.

Larvikitic syenites. Banding in the *Klokken Intrusion* forms an almost perfect saucer-shaped structure in the upper part of the intrusion, with inward dips of

30–50°. The bands, which are concentrations of mafic minerals (olivine and/or clinopyroxene, locally with ore and apatite as well), vary from a few meters to tens of meters thick, and there tends to be a downward gradation from mafic to normal syenite in the units. No "inch-scale" layering is superimposed on the big units. Feldspar lamination parallel to the banding is commonly pronounced.

The pyroxene-fayalite syenites of *Kûngnât* and *Nunarssuit* are notable for their layered structures, and they have many features in common. In both complexes banding is principally developed in the lower part of the exposed syenites: in the Nunarssuit Syenite, however, it is more or less confined to three zones. The lowest, and thickest, of these zones is about 75 m thick. The dip is normally between 15 and 45° towards foci in the centers of the massifs, and in each case it decreases inwards. In the Kûngnât syenites it is clear that the general form of the layering is that of a rather steep-sided dish. Cryptic and phase layering are developed in the Kûngnât Complex (Upton, 1960, pp. 49–50) but have not been detected in the Nunarssuit Syenite.

The layered structures in the Kûngnât and Nunarssuit Syenites comprise mafic banding and feldspar lamination. The latter is seldom developed in the Nunarssuit Syenite owing to the stumpy habit of the perthitic feldspars. The mafic banding is due to concentration of mafic minerals (cumulus clinopyroxene, fayalite and ore—the last commonly having a misleading interstitial form as a result of inter- or adcumulus growth) in plane-parallel layers during periods of magmatic flow. In the Nunarssuit Syenite these layers, where best developed, are 10–30 cm apart and 4–8 cm thick. Gravity stratification is a common but by no means constant feature

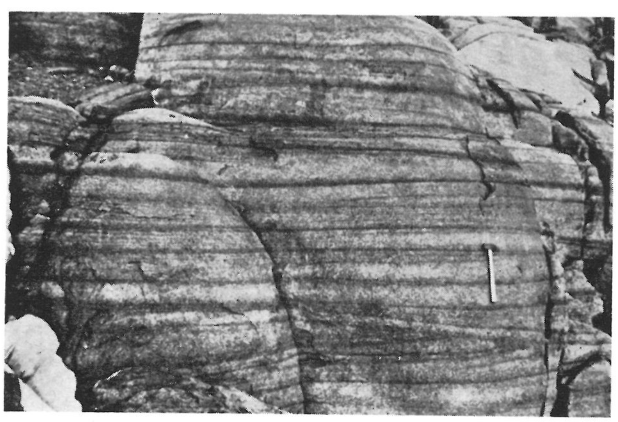

FIG. 3. Rhythmic banding in the Nunarssuit Syenite; note the discordance in the lower part of the photograph.

FIG. 4. Outwash channel cut in regularly banded Nunarssuit Syenite.

of the layered successions, the mafic bands having a well-defined base and passing upwards into less mafic rock. The layers are usually separated by normal syenite. In Kûngnât the units tend to be thicker than in Nunarssuit and may be conspicuously mafic for more than half their thickness.

The Nunarssuit Syenite provides outstanding examples of structures which faithfully mimic those in sedimentary rocks. Discordance—truncation of a layer, or more often a set of layers, by the lowest member of a superincumbent series of rhythmically repeated layers—characterizes the lowest layered zone, and in places gives rise to structures exactly like current bedding.

In conjunction with outwash channels highly pronounced discordances occur (Fig. 4). The channels cut abruptly across the normal planar layers on either side of them and are ascribed to the erosion of a loose cumulate floor. They indicate that the depth of unconsolidated crystal mush must have been at least 2 m.

Both the discordances and the outwash channels are taken as evidence of disturbance due to increased current action during the formation of the layering. Even more spectacular evidence of disturbance is afforded by the slump structures and breccias usually seen near outwash channels. Figure 5 shows disturbed layering which has formed load casts strikingly like structures in the Stillwater complex (Hess, 1960, Pl. 7, lower fig.). Intense disturbance gave rise to breccias (Fig. 6) containing fragments of mafic syenite up to 50 cm long. Some of these

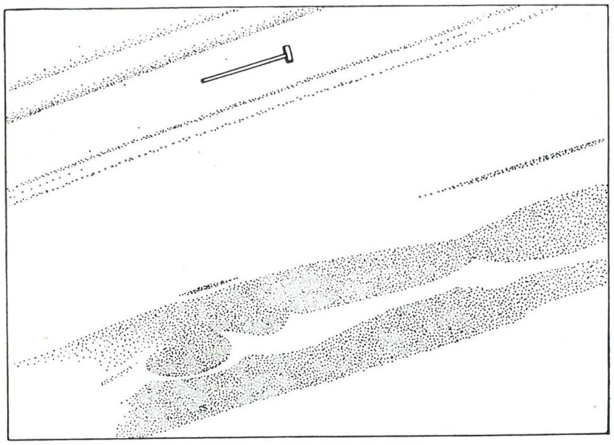

FIG. 5. Mafic layering in the Nunarssuit Syenite. The thicker layers in the lower part of the drawing have been disturbed with the resultant development of load cast-like structures. Drawn from a color transparency.

seem to be fragments of disrupted mafic layers, for they show banding or grading. Others must have been detached from the thick mafic lenses locally associated with trough banding, for they are homogeneous and too thick to have been derived from the usual sort of layering in the syenite. The breccias may lie concordantly above or below undisturbed banding; on the other hand in places they truncate such banding. In one layered sequence the dip of each successive layer increases from about 35 to 45°, passing up the succession which terminates abruptly in an overlying slump breccia zone. This points to a value of about 45° for the maximum angle of rest of the cumulate floor. For the Kûngnât syenites Upton (1960, p. 116) gives 40–50° as the maximum angle of rest under normal conditions. These figures are very much higher than those given by Brown (1956, p. 38) for the ultrabasic cumulates of Rhum, where the maximum angle of rest seems to have been only 15°.

Similar, if less spectacular, evidence for magmatic flow can be seen in the Kûngnât syenites. In addition they display trough banding closely resembling that in the Skaergaard intrusion (Wager and Deer, 1939) but not strictly comparable with the outwash channels in Nunarssuit. The troughs, which are up to 12 m wide, are typically bilaterally symmetrical; their axes are directed towards the center of the intrusion and inclined at the same angle as the layering. Rhythmic mafic layering is seen in the trough bands, and the trough-like form may be preserved through up to 30 units, although the degree of crystal sorting and strength of banding diminishes upwards through the trough set (Upton, 1960, fig. 15).

The border syenites of eastern Kûngnât are characterized by the possession of steep fluxion-banding. This takes the form of rather wispy mafic bands, seldom thicker than 2 cm, usually dipping steeply into the intrusion and striking approximately parallel to the contact. In detail the course of these bands is highly irregular.

Steep mafic layering striking parallel to the border of the intrusion also occurs in the marginal augite syenite of the *Ilímaussaq Intrusion*. The mafic concentrations are 1–3 cm thick and are separated by 2–30 cm of the normal rock; considered individually they are of remarkably constant thickness. In contrast to the fluxion-banding at Kûngnât, this banding is very even, the only irregularity being a slight tendency for bands to merge up-dip. The bands wedge out towards the margin against the fine-grained chilled syenite and inwards in a coarse-grained facies of augite syenite. The angle of dip (50–75°) is steeper than the maximum angle of rest of the cumulate floor in the comparable augite syenites of Kûngnât and Nunarssuit; this argues against magmatic currents assisted by gravity having caused the layering. Rather it seems that mafic nuclei were repeatedly precipitated and grew on the cooling side of the magma chamber. The necessary periodicity could be the result of regular rapid oscillations in the water vapor pressure of the magma (Yoder, 1954) or be developed as an intrinsic part of the nucleation process, if supercooling of the

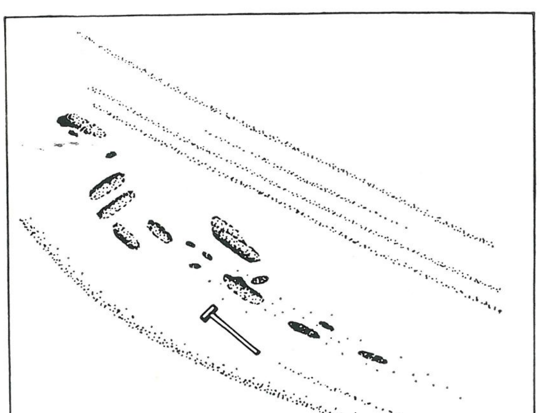

FIG. 6. Slump breccia in the Nunarssuit Syenite. The fragments in the breccia are of banded and gravity stratified syenite which has been broken up during strong disturbances. Drawn from a photograph.

magma initiated nucleation (Wadsworth, 1961, p. 61).

In the Ilímaussaq Intrusion pulaskite and quartz syenite, believed to be hybrid rocks formed by reaction between alkali granite and earlier undersaturated rocks, form sheets which show banding on rather a fine scale. In the pulaskite the banding is due to the concentration of arfvedsonite and small amounts of olivine in dark bands averaging a centimeter thick, separated by 2–3 cm thick bands of feldspathic syenite. In the quartz syenite the banding is similar but only arfvedsonite is concentrated in the dark bands. Thin sheets (*i.e.* less than 2 m thick) may be banded throughout their entire thickness and the banding may extend laterally over 50–100 m. Lamination is never seen in these layered rocks. In one instance a discordance in the banding at the center of a sill suggests that growth took place simultaneously from both sides of the sill towards the center.

A heterogeneous syenite characterized by very uneven grain size occurs between the augite syenite and agpaitic rocks of Ilímaussaq. In it the rock-forming minerals are perthite, soda-pyroxene, soda-amphibole, olivine and nepheline. Banding is sporadically developed due to alternation of bands about a meter thick of coarse rock relatively rich in olivine with lighter pegmatitic bands in which feldspars averaging 6 cm×1 cm tend to be aligned with their long axes perpendicular to the banding. Fragments of the coarse rock, 20–30 cm in diameter, are commonly included in the pegmatitic bands, particularly where the latter are slightly transgressive.

This heterogeneous syenite is considered to have crystallized from the roof downwards. The banding may best be explained by repetitive volatile accumulations at the base of the downward crystallizing rock which resulted in the formation of the pegmatitic bands. The same mechanism, working upwards, is envisaged by Weedon (1960, pp. 46–47) to account for the pegmatitic bands in the Gars-bheinn sill of Skye.

Nepheline syenites

(a) The Ilímaussaq Intrusion

A brief review of the evolution of the Ilímaussaq Intrusion is essential to the understanding of the igneous banding in the agpaitic rocks. The schematic diagram (Fig. 7) illustrates the structure as interpreted by the one author (Ferguson, in press). The earliest magma in the intrusion had an augite

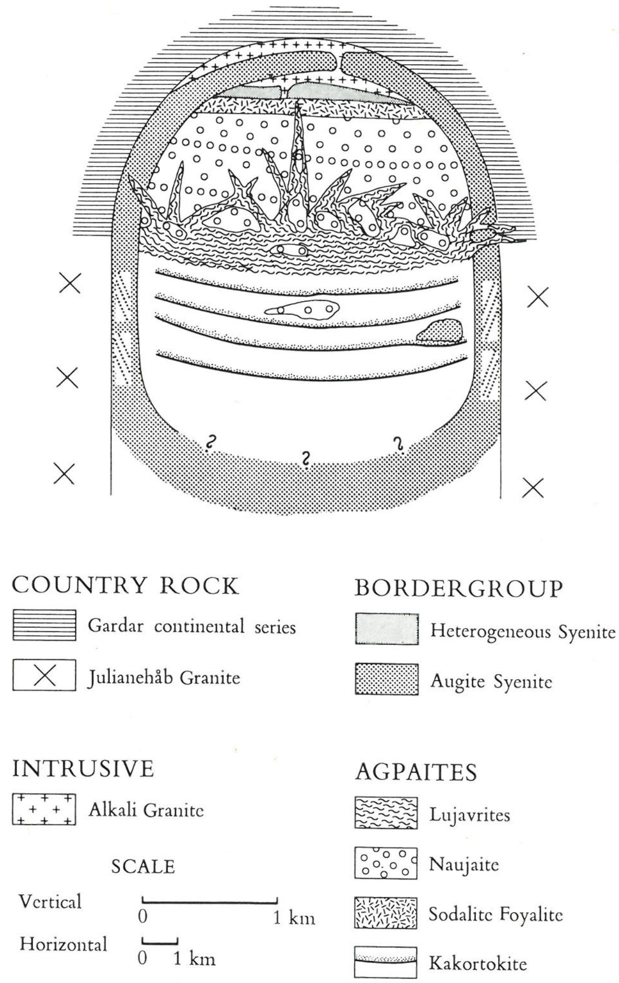

Fig. 7. Diagrammatic cross section of the Ilímaussaq Intrusion.

syenitic composition. After emplacement this magma proceeded along an undersaturated differentiation trend. The layering in the early derivatives has already been described. The *in situ* differentiation was interrupted by the injection of alkali granite into the upper part of the intrusion. Following this undersaturated differentiation was resumed and, aided by volatiles, formed magma of per-alkaline (agpaitic) composition. Crystallization of the agpaitic magma took place from the roof downwards with simultaneous bottom accumulation on the floor of the intrusion. Finally a residual crystal mush, rich in volatiles, was trapped between the downward crystallizing naujaite and the bottom-accumulated kakortokites. As a result of deformation the residual crystal mush was injected into the overlying brecciated rocks. This residual magma crystallized to from the fissile lujavrites.

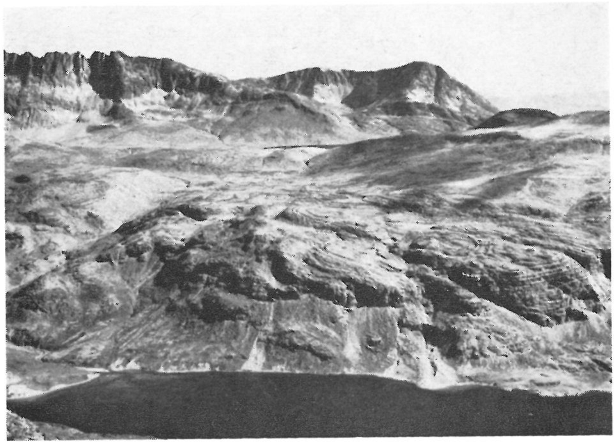

FIG. 8. Main occurrence of the layered kakortokites.

(i) Kakortokite. The kakortokites are the layered agpaitic rocks exposed in the lowermost part of the intrusion (Figs. 8 and 9). The layering comprises rhythmic compositional variations developed through a vertical thickness of more than 400 m of the exposed part of the kakortokites. Within this there are approximately 25–30 layered units, each unit consisting of black, red and white bands corresponding to arfvedsonite/aegirine, eudialyte and alkali feldspar concentrations respectively. The white kakortokite bands have an average thickness of 10 m whereas those of black and red kakortokite average 1.5 m thick. The upward sequence black-red-white is never varied, even though the red bands may be inconspicuous.

Modal analyses from the different bands indicate the compositional variations responsible for the banding.

	Perthite	*Aegirine*	*Arfvedsonite*	*Eudialyte*	*Nepheline*
White kakortokite	50	9	13	10	18
Red kakortokite	36	6	12	29	17
Black kakortokite	18	13	40	11	18

The base of each unit is usually rather sharply defined, the transition between the underlying white kakortokite and the black kakortokite taking place in 5–10 cm or even less. In one case it is knife-sharp. The black kakortokite passes up into red kakortokite through a 15–25 cm thick transition zone in which there is a rapid increase in the proportion of eudialyte and feldspar. Eudialyte, concentrated at the bottom of the red bands, becomes less plentiful passing up into the white kakortokite.

The layers are considered to have been originally horizontal, but due to sagging are gently undulating. They are very persistent, and individual bands maintain a constant thickness over the whole area of the kakortokites to within 50 m of the margin, where they wedge out in a coarse-grained rock. Where inclusions of older rock are found, the underlying layers are compressed (Fig. 9), in one instance to approximately $\frac{2}{3}$ds of their original thickness to a depth of 15–20 m below the inclusion. This is significant, as it indicates that the depth of unconsolidated crystal mush must have been about 20 m. The overlying layers pass conformably over the inclusions without thinning at the crests.

In the black bands there is marked lamination produced by the 4 mm$\times$1 mm tabular feldspars and prisms of arfvedsonite or aegirine of similar size lying in the plane of the banding. There is no lineation within the plane of lamination. Less pronounced feldspar lamination is developed in the white kakortokite. The finer-grained red kakortokite tends to have a saccharoidal texture.

The microscopic texture of the black bands suggests that in the black kakortokite all the minerals are cumulus. In the red and white bands feldspar, nepheline and eudialyte are the cumulus minerals whereas arfvedsonite and aegirine are poikilitic. Some idea of the original size of the cumulus nepheline and eudialyte in the latter two bands can be gained from the crystals enclosed in the arfvedsonite and aegirine. These are as little as half as large as the crystals not enclosed, which have increased their size by adcumulus addition. The same approach cannot be applied to the perthite crystals, which are too large to be completely enclosed in the arfvedsonite and aegirine.

But for a few crystals of concentrically-zoned

FIG. 9. Banded kakortokite with an inclusion of foreign rock which has compressed the underlying layers. (Photograph by F. L. Jacobsen.)

eudialyte and albite rims on some perthites, zoning is lacking in the minerals of the kakortokites. This suggests that the cumulus crystals grew by adcumulus addition. Diffusion from the overlying magma into the crystal pile must have taken place over distances up to 20 m, since this is the depth of unconsolidated crystal mush.

The only evidence of cryptic layering is provided by the nepheline. Passing up the kakortokites the $\%KAlSiO_4$ diminishes irregularly from 18.5 to 9.6. No phase layering (Hess, 1960, p. 132) occurs.

Ussing (1911) advanced the following hypothesis for the formation of the kakortokites "... the simplest supposition is perhaps that the recurrent layers have originated in consequence of repeated variations in pressure" (p. 361). Experimental work by Yoder (1954) on the system diopside-anorthite-water has demonstrated that variations in water vapor pressure could produce layering. The Ilímaussaq Intrusion was emplaced high into the Gardar sandstones and lavas and is thus a high-level intrusion. Intermittent water vapor pressure release could have easily taken place through fissures or conduits which penetrated to the surface. A small shift in the eutectic caused by a change in water vapor pressure and resulting in arfvedsonite and aegirine crystallizing first would account for the cumulus nature of these minerals in the black bands.

The units in the kakortokite are gravity stratified.

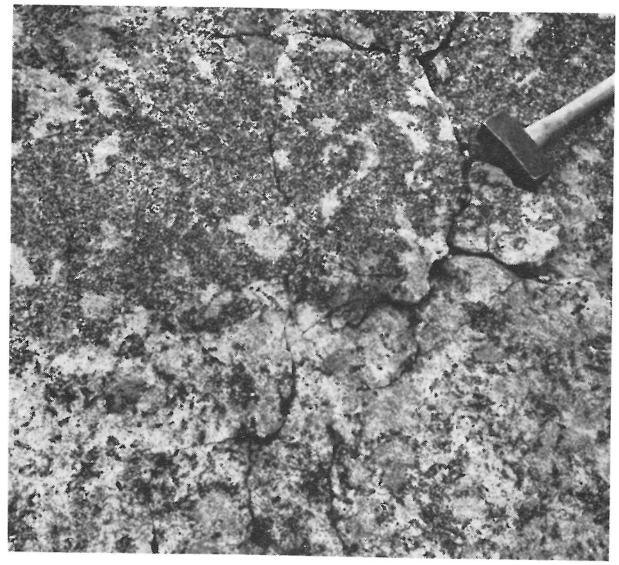

FIG. 11. Close-up of the naujaite banding seen in Fig. 10, showing the upper part of a light band and the lower part of a dark band. Note the large aegirine/arfvedsonite anhedra in the latter.

To account for this, Upton (1961, p. 12) suggested that the black kakortokites have formed during periods of flow sufficiently strong to have retained the feldspar in suspension. However it might be possible to produce density grading without resorting to magmatic flow. In the agpaitic magma, which had a very high volatile and water content, an increase in density would accompany increase in total pressure,

FIG. 10. Banding in naujaite involving compositional and textural variations.

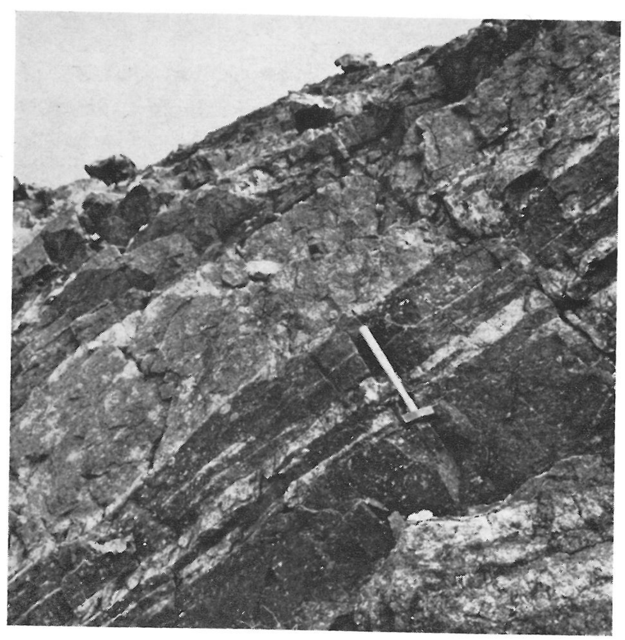

FIG. 12. Alternating aegirine (light) and arfvedsonite (dark) lujavrite bands.

particularly if some of the volatile components were in fine bubble suspension. The sinking rate of the minerals would be retarded by such a density increase in the magma, and the reduction of sinking rate would be most marked in the case of the feldspars, the density of which was close to that of the magma. Variations in total pressure could therefore account for the density stratified layering, the black bands corresponding to periods of high pressure and higher density of the magma, while the feldspathic bands correspond to periods of low pressure and lower density.

Thus the layering in the kakortokites may have originated as a result of variations either in the water vapor pressure of the magma or in total pressure in the magma chamber, or it may be due to simultaneous fluctuations in both forms of pressure.

Discordances, outwash channels and other evidence of the strong currents and turbulence which are regarded as responsible for gravity stratification in some layered igneous rocks (*e.g.* the Nunarssuit Syenite), are lacking in the kakortokites. Upton (1961, p. 28) claims to have observed "incipient trough banding" and minor disconformities in the kakortokites, but these were not observed by the first author. Conditions obtained which allowed undisturbed accumulative settling on the floor of the magma chamber. This is in contrast to the Skaergaard intrusion where convection currents operated during crystallization, hence the analogies with the kakortokites are not as close as Wager and Deer (1939, p. 289) imply.

(ii) Naujaite. Ussing (1911, pp. 349–354) was of the opinion that sodalite was one of the first minerals to crystallize in the magma chamber and that it floated due to its low density. He considered the naujaite to have formed by the flotation of sodalite crystals which were trapped in a downward crystallizing rock, giving rise to the poikilitic texture which characterizes the rock. This theory agrees with the new interpretation of the evolution of the intrusion since the bottom-accumulated kakortokites are virtually free of sodalite. The average naujaite is made up of poikilitic feldspar, aegirine, arfvedsonite and eudialyte of pegmatoid dimensions with 2–3 cm diameter sodalite inclusions which make up 34–45% of the rock.

Banded horizons have been observed throughout the *ca.* 1000 m thickness of exposed naujaite. They are flat-lying except near the border of the intrusion where there are locally steep inward dips. The commonest banding is produced by compositional variations which are usually associated with textural change. Dark bands 60 cm to a meter thick, rich in aegirine and arfvedsonite, alternate with thicker feldspar-rich bands, with local 5–10 cm eudialyte-rich bands intervening. The poikilitic texture of the normal naujaite is retained in these bands, but the aegirine/arfvedsonite anhedra are of different sizes in the different bands. In the dark bands the aegirine/arfvedsonite forms the usual 10 cm diameter anhedra found in the normal naujaite, but in the light bands these minerals form prisms 2–3×1 cm.

Aegirine/arfvedsonite concentrations 20–30 cm thick set a meter apart in normal naujaite are also common. The aegirine/arfvedsonite in the dark bands forms 2–3×1 cm prismatic crystals.

Sodalite-rich and sodalite-poor horizons are developed locally in the naujaite. The sodalite-rich bands (termed sodalitites by Ussing) vary from 0.5 to 5.0 m thick and may contain up to 70–80% sodalite which is of the same size as, or a little smaller than, that in the normal naujaite. The remaining minerals—any of those found in the normal naujaite—are skeletal due to the excessive amount of sodalite inclusions. Commonly sodalitite forms a single horizon within the normal naujaite. However sodalite-rich bands can alternate with light bands rich in poikilitic feldspar and eudialyte.

The 10–20 cm thick sodalite-poor bands occur singly within normal naujaite. They do not have a poikilitic texture; instead sodalite forms scattered xenomorphic crystals measuring up to a few centimeters across.

Narrow, less than 1 m thick, asymmetrically-zoned lenticular pegmatites are sporadically found in the naujaite, having conformable relations to the banding. They have been described by Sørensen (1962).

The naujaite is a flotation cumulate. As the naujaite and kakortokite crystallized simultaneously at the top and bottom respectively of a single magma chamber, the same pressure variation affected the crystallization of both. The layering in the naujaite comprising light and dark bands with local red bands is interpreted as being complimentary to the banding in the kakortokites and caused by the same fluctuations in pressure conditions. The sodalite-rich bands could have been formed during periods of excess sodalite formation and/or efficient flotation. Flotation would have been assisted by increase in density of the magma resulting from pressure increase (see under *kakortokites*). Conversely the sodalite-poor bands could have been produced during short periods of arrested sodalite flotation, which allowed the magma to crystallize without the addition of cumulus sodalite.

(iii) Lujavrites. The lujavrites are the youngest agpaitic rocks of the Ilímaussaq Intrusion. Unlike the other nepheline syenites, they are rather fine-grained and possess a strong fissility due to acicular aegirine and arfvedsonite crystals up to 3 mm long, lying in a common plane. Lineation is rare in the plane of lamination. In addition to aegirine and/or arfvedsonite, which make up 30–40% of the rock, the lujavrites contain microcline and albite in separate crystals, nepheline, sodalite and eudialyte. They may be divided into two types: green aegirine lujavrite and black arfvedsonite lujavrite.

The lujavrites form a unit *ca.* 200 m thick between the naujaite and kakortokites. The lower half of this unit is occupied by green lujavrite, the upper by black lujavrite. Banding is developed principally in a 50 m thick mixed zone in between. The banded sequences do not exceed 40 m and are usually only 2–5 m in thickness. Within these the bands vary from 1 cm–15 m thick, averaging 10 cm; they are lenticular and may have marked pinch-and-swell structure. Auto-intrusion has resulted in banded lujavrite being cross-cut by dikes of inhomogeneous lujavrite.

Of the different types of banding developed, that due to alternation of aegirine and arfvedsonite lujavrite involves no textural variations. In the banding produced by the alternation of layers rich in feldspar with darker layers, the latter show density stratification (Fig. 13). For example, at the base of the darker band there may be 3–4 mm of only arfvedsonite; passing upwards light minerals enter into the rock and gradually become more plentiful. Here and there the dark bands grade into the overlying light bands, but more commonly there is a distinct break between the two bands. Only one case of compositional banding accompanied by textural variations was observed; this was in coarse-grained green lujavrite which contains bands rich in feldspar.

It is postulated that aegirine, feldspars, eudialyte and nepheline formed the cumulus minerals in a residual volatile-enriched magma and accumulated on top of the kakortokites to form the green lujavrite. After about half of the residual magma had crystallized, arfvedsonite began to form instead of aegirine. Alternation in the formation of the two minerals produced black and green banded lujavrite. This is the only example of banding in south Greenland where water vapor control is a probability rather than a possibility. Yagi (1953) has inferred that the order of crystallization of aegirine-augite and arfvedsonite depends on the presence of volatiles, especially water, which favors the crystallization of arfvedsonite, and Fyfe *et al.* (1958, pp. 162–163) have proposed stability relations for OH- and F-bearing amphiboles and pyroxene which are dependent on water vapor pressure. In the concluding stages of crystallization the residual magma rich in volatiles crystallized as black arfvedsonite lujavrite.

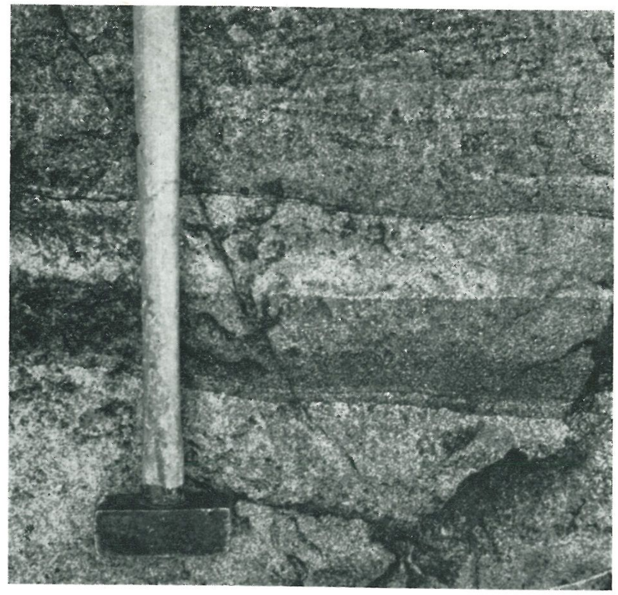

FIG. 13. Alternating bands of dark arfvedsonite-rich lujavrite showing density stratification and light feldspathic lujavrite bands.

The intercumulus areas in the lujavrites are thought to have had a high volatile content which served to keep the cumulate in a mobile state. As a result on deformation (faulting and/or sagging) the crystal mush was compressed and some of it injected into the overlying brecciated rocks, finally crystallizing as fissile lujavrites. The volatile phase was squeezed out to form late-stage natrolite-analcime veins. The various inhomogeneities in the crystal mush were streaked out into bands during deformation, and the size and density sorting locally seen are thought to have been produced during flowage (*cf.* Wilshire, 1961).

(b) The Grønnedal-Ika Complex

The majority of the Grønnedal-Ika nepheline syenites is foyaitic with pronounced igneous lamination dipping at various angles towards the center of the complex. Callisen (1943) considered that gravitational differentiation was a significant factor in their crystallization history; on this assumption and from the close textural similarities with rocks from layered intrusions, the main cumulus phases were nepheline and platy crystals of alkali feldspar, with intercumulus aegirine-augite, biotite, cancrinite, fluorite and carbonate. A minor amount of mineral layering concordant with the lamination occurs at one level within the foyaites. In thin bands of relatively mafic rock aegirine-augite and apatite join the cumulus phases and an alkali amphibole appears in an intercumulus role. Possible complementary rocks are rare perthosites with very well-developed lamination.

In another variety of layering, impersistent horizons of altered, poorly laminated syenite occur conformable to the lamination in fresh foyaite. The poorly laminated syenites and the associated foyaites are thought to represent respectively loose and closely packed bottom accumulates, resulting from slight variations in the strength of magmatic currents during crystallization; greater alteration of the ill-packed rocks is attributed to a high proportion of intercumulus liquids.

Granite. Mafic layers from one to roughly twenty centimeters thick occur locally in the *Helene Granite* of the Nunarssuit Complex (Harry and Emeleus, 1960; Harry and Pulvertaft, 1963). Those up to about two centimeters thick are simply concentrations of the mafic, and some accessory, minerals found in the normal granite. Of these the clinopyroxene and, where present, fayalite are cumulus minerals. Hornblende, although plentiful in the dark bands, is to some extent a replacement of pyroxene and probably owes its abundance to such processes rather than accumulation of a primary precipitate. The thicker mafic layers are even-grained rocks in which quartz and feldspar are rather finer-grained than in the normal intervening granite. The layers can be symmetrical or asymmetrical in cross section: asymmetrical bands have a sharp base, grading up into normal granite. Preferred orientation of mineral form is seldom apparent in the layered rocks or indeed in the granite as a whole, but elongate xenoliths locally present are arranged parallel to the layering.

The mafic layers in normal Helene Granite may be rhythmically repeated within a single exposure to give a succession of up to about thirty sub-parallel bands a fraction of a meter apart. These mafic layers can be traced continuously for distances of up to 14 m and generally terminate by wedging out. Less commonly layers may be isolate, commonly branching individuals, the traces of which may describe graceful arcs. In some places a rhythmically repeated succession is arcuate in vertical profile and recalls trough banding. The attitude of the layering in the Helene Granite is variable; both steep and moderate dips have been observed.

On the whole the analogies between the mafic layering in the Helene Granite and that in the Kûngnât and Nunarssuit syenites are sufficient to justify the view that the layering in the granite is primarily due to the accumulation of dark minerals under the influence of gravity and magmatic currents. The irregularities and steeper dips met with in the granite are what would be expected if the granite magma, although fluid enough to allow currents, was more viscous than a pyroxene-fayalite syenite magma.

Another type of layering, involving textural variations (bands of porphyritic granite and microgranite) as well as mafic bands and normal granite, is seen at two localities in the Helene Granite. Very thin mafic layers are remarkably persistent in these banded zones. Some kind of repeated differentiation *in situ*, rather than currents, appears to have governed their formation.

Conclusions

The great variety of layered features displayed in the Gardar intrusions is apparent from the foregoing section. Obviously more than one factor was responsible for the development of the layering.

The striking similarity between the layered structures in the Kûngnât and Nunarssuit syenites and those in sedimentary rocks allows it to be confidently stated that the layering in these syenites is primarily the result of magmatic current action. The Helene Granite most likely owes much of its banding to the same mechanism. The feldspar lamination developed in many other intrusions indicates that in these crystallization was accompanied by gentle magmatic flow or alternatively took place in a magma of rather low viscosity in which the feldspars would settle flat on the cumulate floor without the assistance of currents. Thus the Gardar magmas for the most part possessed high mobility, as has already been pointed out by Upton (1961, p. 10). The widespread occurrence of fluorite in the Gardar intrusions testifies to high fluorine content in the magmas which would reduce their viscosity (Buerger, 1948). In many Gardar intrusions, however, current action was of little or no importance.

The fact that many Gardar centers were high-level intrusion likely to have had access to the surface is believed by the authors to have been the other main cause for the common incidence of layering in these intrusions. The Ilímaussaq and Igaliko intrusions were both emplaced into the Gardar continental series, and around Narssaq the giant dikes of Tugtutôq pass up into sills in these supracrustal rocks. The unbanded Central Complex of Tugtutôq contains blocks of basalt and quartzite clearly derived from the supracrustal series and must therefore have penetrated up into these. In such intrusions optimum conditions existed for cyclic fluctuations in water vapor pressure. That such fluctuations could produce layering was suggested long ago by Ussing.

However it should be pointed out that in many other parts of the world there are high-level intrusions which do not show layering or in which layered structures have not been recorded in rock less basic than gabbro. In this latter respect the Gardar Province is unique.

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