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The origin of igneous layering in the Nunarssuit syenite, South Greenland

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ABSTRACT

The rhythmic modal layering in the Nunarssuit syenite has a vertical extent of >150 m and a lateral extent of >15 km. Individual layers average 20 cm thick and grade from a relatively melanocratic base into more leucocratic syenite over a distance of up to 5 cm. The major cumulus phases are alkali feldspar, ferro-salite/hedenbergite and fayalite. Two basic stratigraphic cycles have been identified in which faint modal layering becomes more pronounced up section, each cycle terminating in a thick melanocratic zone. Slumps, slump breccias, troughs, micro-rhythmic layering and one occurrence of crossed layers were observed.

Qualitative grain size analysis indicates no size sorting in the layers. Preliminary application of crystal size distribution theory to ferro-salite/hedenbergite and fayalite from the bases of individual layers gives results which may be interpreted as indicating a relative lack of coarse grains. If the layers were deposited from density currents it would be expected that the coarsest grains would be deposited close to the source of the currents. There is no evidence in the majority of the syenite that the cumulus pile underwent compaction during crystallization.

There was little, or no, primary chemical variation across individual layers. Whole-rock compositions and the ferro-salite/hedenbergite, fayalite, biotite and amphibole present in the syenites show a slight, but statistically significant, increase in the ratio Mg/(Mg+Fe_{total}), from the base up to the top of the layered succession.

A model is suggested in which successive magma layers become more ferroan towards the top of the chamber. Cooling is concentrated at the top of the chamber and layers of magma crystallize sequentially, the uppermost, ferroan layers first. As layers of magma cool and crystallize they sink, as crystal-melt plumes, to the bottom of the chamber where they source density currents from which layers are deposited.

Keywords: Greenland, igneous layering, crystal settling, syenite.

Introduction

The Nunarssuit complex is part of the Gardar alkaline province in South Greenland (Harry and Pulvertaft, 1963, their Plate 1). The Nunarssuit syenite has a Rb–Sr age of 1154 ± 14 Ma (Blaxland *et al.*, 1978). The exposed outcrop measures 45 km by 25 km. It is notable because of the well developed igneous layering that can be seen long the coastal edge of the Davis Strait.

Reviews of the regional geology of the Gardar province have been published by Upton, (1974), Emeleus and Upton, (1976) and Upton and Emeleus, (1987). Ferguson and Pulvertaft (1963), and more recently Upton *et al.* (1996), reviewed the variety of layering phenomena observed in the province. The first detailed work on the Nunarssuit syenite was carried out by the Geological Survey of Greenland (Harry and Pulvertaft, 1963). Since 1963 the Nunarssuit intrusion has been studied by Anderson (1974), Butterfield (1980), Parsons and Butterfield (1981) and Hodson (1994). Greenwood (pers comm.) demonstrated on the basis of mineral composi-

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tions that the 24 km by 13 km island of Nunarssuit consists of five arcuate bodies of syenite (Emeleus and Upton, 1976). Of these it is only the outermost, coastal, unit on Nunarssuit that exhibits any notable layering (Parsons and Butterfield, 1981, their Fig. 1). Normally-graded rhythmic and micro-rhythmic modal layering, slump structures, breccias and trough structures are present (see Irvine (1987*a*) for a comprehensive description of terms). The lateral extent of the layered series is at least 15km. Basic questions such as whether igneous layers formed *in situ* or if they consist of crystals which formed elsewhere and were then transported are still unanswered (cf. Parsons, 1987; Cawthorn, 1996).

Field work for the present study was carried out in an approximately 2 km^2 area north of the fjord Tasiussaq at approximately 60°43′N 48°5′E, (Fig. 1). This paper describes the igneous layering phenomena observed on a SW–NE traverse through the layered sequence (Fig. 1) and presents a new stratigraphy for the layered series. The issue of crystal settling, specifically in syenitic magmas, is addressed and new data which indicate that the Nunarssuit layered syenite exhibits inverse cryptic layering are presented. Finally a hypothesis is proposed to explain the Nunarssuit layering which takes into account the observed stratigraphy and the inverse cryptic layering.

Layering phenomena observed in the syenites of SW Nunarssuit

Normally-graded modal rhythmic layering is present from the south coast to the south-facing cliffs labelled in Fig. 1. To the east the layering becomes less well defined. The normally-graded layers have a well-defined melanocratic base (colour index of *c*. 20–30%), where ferro-salite/hedenbergite, fayalite, annite and barkevikite are concentrated relative to alkali feldspar, and grade up into more leucocratic 'normal' syenite (colour index of *c*. 10–20%) over a distance of a couple of centimetres. The thickness of an individual layer varies between 5 and 80 cm and is *c*. 20 cm

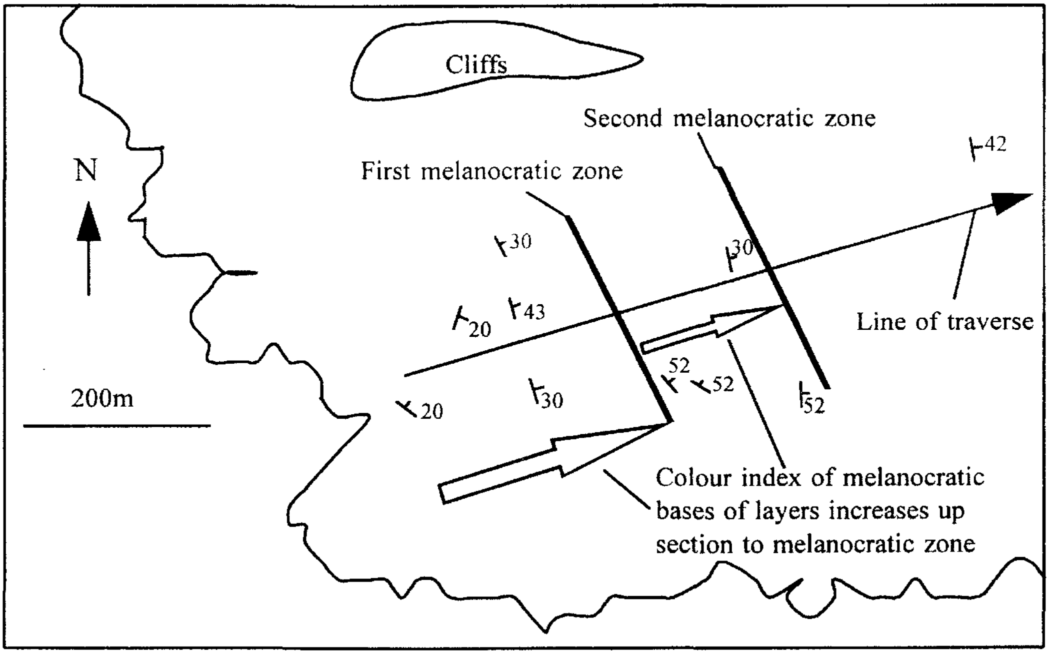

FIG. 1. Sketch map of field area showing the traverse taken through the layered zone, and some dip and strike measurements on the layering.

on average but varies along strike. The majority of the layers observed are continuous along strike over a distance of several hundred metres. However, some layers are discontinuous, the melanocratic base terminating abruptly along strike. Commonly their place is taken up, within a few tens of centimetres at the most, by another layer at a similar stratigraphic level, the two layers rarely overlap. Truncations of layers, or sets of layers, by the lowest member of the overlying series of layers are common (e.g. Fig. 2*a*).

All the layers measured in the field area dip at between 20 and 50° to the east with a strike of between 315° and 010°. Harry and Pulvertaft (1963) carried out extensive structural measurements over the entire Nunarssuit syenite and showed that the strike of the layering defines an arc about a point in central Nunarssuit. This, together with the similarity of the layering to that seen in the West Kûngnât syenite (Upton, 1960), led Parsons and Butterfield (1981) to suggest that the dip of the layering was primary.

Structures which resemble troughs seen in the sedimentary record, are observed. These structures, which will be referred to as troughs, vary in scale between tens of centimetres and several metres and do not appear to disturb the layering around them; in places the trough 'wing tips', i.e. the tapered edges of the trough infill, appear to be continuous with the adjacent layering. The troughs are usually filled with melanocratic material.

Slump structures and breccias are concentrated within and immediately below two thick melanocratic zones in the stratigraphy (Fig. 1 and see below). A striking example of slump structures is shown in Fig. 2*b*. The bases of these two slumps appear to be erosive, cutting into the adjacent layering. Both slumps contain small (*c.* 10 cm scale) clasts of melanocratic layered syenite. The lower slump is graded, being more melanocratic at its base, whereas the upper slump is more chaotic, containing convolutions of normal and melanocratic syenite. Rhythmic modal-layering is observed above and below the two slumps. Smaller scale slumps are also observed (e.g. Fig. 2*c*). Slump breccias containing black ultramafic clasts up to tens of centimetres in scale, were also observed, e.g. Fig. 2*d*. The clasts are frequently layered. Although no source for these clasts was observed it is thought that these clasts are fragments of disrupted melanocratic layers and they will be referred to as autoliths.

The melanocratic material in the troughs, slumps and autoliths is more melanocratic than the material seen in the bases of the modal layers and the feldspar is sometimes present as oikocrysts around smaller pyroxene crystals.

Structures are also observed which do not have an obvious analogue in the sedimentary rock record. For example in Fig. 2*e* rhythmic layers run from the top right to bottom left of the picture whilst a second arcuate and modally graded layer is seen in the top left of the picture which cuts the first set. The syenite in the centre of the arcuate layer resembles normal syenite.

Only one example of well-developed microrhythmic layering was observed (Fig. 2*f*). This occurred below the first thick melanocratic zone. Individual layers consist of a thin melanocratic base, about 1 cm thick, which grades up into normal syenite within another centimetre; layers are approximately 3 cm apart.

Discussion of the layering phenomena

Despite their resemblance to sedimentary structures it should not be taken for granted that all the structures seen in the Nunarssuit syenite formed by processes which have an analogue in sedimentology. However, it is hard to imagine other processes by which these structures could have formed.

Layers which die out along strike are consistent with deposition of crystals from a crystal-laden current flowing along the floor of the chamber, a layer-producing mechanism suggested by Irvine (1987*b*) for the layering observed at Skaergård. Such currents would have a finite width and layering would die out at the edges of the currents. The depletion in the coarsest grain fraction of clinopyroxenes and olivines in the melanocratic bases of layers (see below) lends weight to this argument. As the crystals transported in the current are carried further away from the source of the density current, grains would be deposited, the coarsest and most dense fraction first.

The currents could have had their source in crystal-laden plumes sinking from the top of the magma chamber, or the collapse of unstable piles of crystals which build up beneath either descending crystal-melt plumes or the wall-parallel boundary layers at the edge of the magma chamber (Irvine, 1987*b*). Experiments have shown (Bak and Chen, 1991) that a pile of unconsolidated grains, growing by the deposition

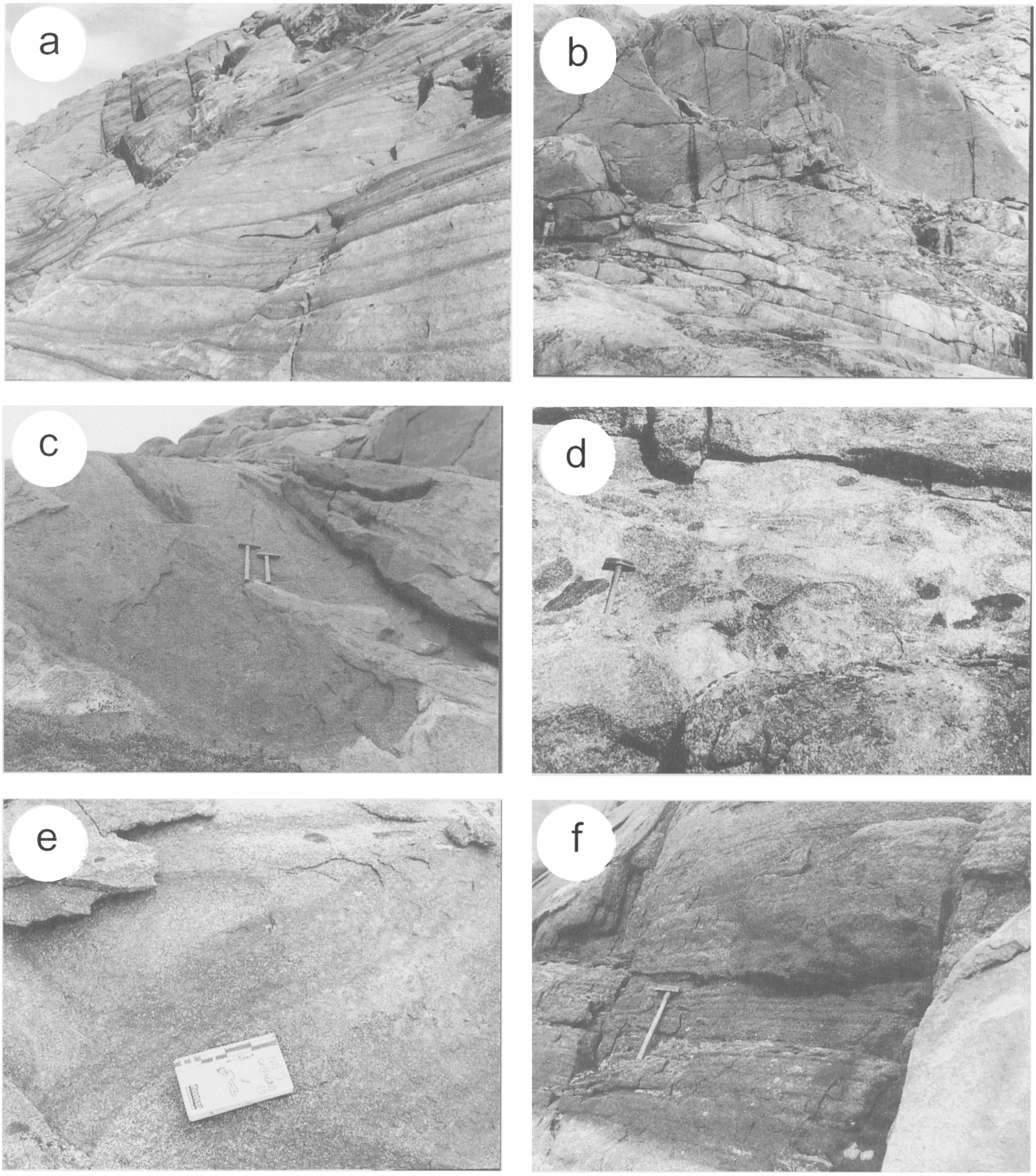

FIG. 2. Photographs illustrating sedimentary-style structures in the Nunarssuit layered syenite. (*a*) Normally graded rhythmic layers. Various sets of layers are truncated by an over-lying layer. On the left of the picture a set of troughs is visible; (*b*) Two overlapping slumps. Layer formation was interrupted by the deposition of two large slumps, probably representing a crystal-melt slurry generated by wall collapse. Both troughs have an erosive base. Rhythmic layering is visible below the slumps; (*c*) Slump structure, syenite within the slump near the hammers is layered; (*d*). Slump breccia. Dark blobs are mafic to ultramafic cumulates thought to have been transported from the wall of the chamber, after wall collapse, by a crystal-melt slurry; (*e*) Crossed layers. One set of rhythmic layers runs from the top right to the bottom left of the picture. The other set of layers curves in the top left towards the centre of the picture; (*f*) Micro-rhythmic layering.

of grains onto the top of the pile, will attain a critical slope. After the critical slope has been attained the addition of grains will generate avalanches involving varying numbers of grains. It is possible that an analogous process happens in magma chambers with piles of crystals accumulating below side-wall boundary layers. The episodic avalanching of grains could be the source of the debris-flow currents from which layers are deposited. The assumed 30° slope of the chamber floor (Parsons and Butterfield, 1981) would have reduced the amount of energy needed for the forward propagation of these debris-flows. If crystals accumulated on the piles at a fairly regular rate then avalanches might also occur at a fairly regular rate, thus explaining the fairly regular spacing of layers.

Truncations of layers (Fig. 2*a*) could have been produced by erosion of the crystal pile by a convection current or a crystal-melt density current and the deposition of another layer on the new floor in a similar fashion to the generation of low-angle cross bedding in fluvial deposits (Tucker, 1981).

The presence of layered melanocratic autoliths in slump breccias (Fig. 2*d*) implies the existence of layered melanocratic syenite prior to the formation of the layered series described in this paper. The bulk chemistry of samples from the melanocratic zones and melanocratic autoliths plot on the same trends as the rest of the syenite seen in the layered succession but are more mafic (Fig. 3). These facts, together with the resemblance of many of the melanocratic structures to slumps in the sedimentary record, makes the author favour the early crystallization of a melanocratic syenite sidewall cumulate and its subsequent detachment from chamber walls, or the roof, and downwards transport as slurries, as the source of the various slumps and troughs seen. The merging of layers into trough wing tips is taken as evidence that both layers and troughs were generated by flows of crystals across the chamber floor. The layers are the product of widely distributed flows whilst troughs are the products of flows across a more restricted width of the chamber floor. The detachment of the sidewall cumulates could be due simply to the pull of gravity (i.e. wall collapse) or alternatively it could be triggered by eruption of the magma chamber, faulting or intrusion of more magma. The vertical height of some of the slump structures seen (e.g.

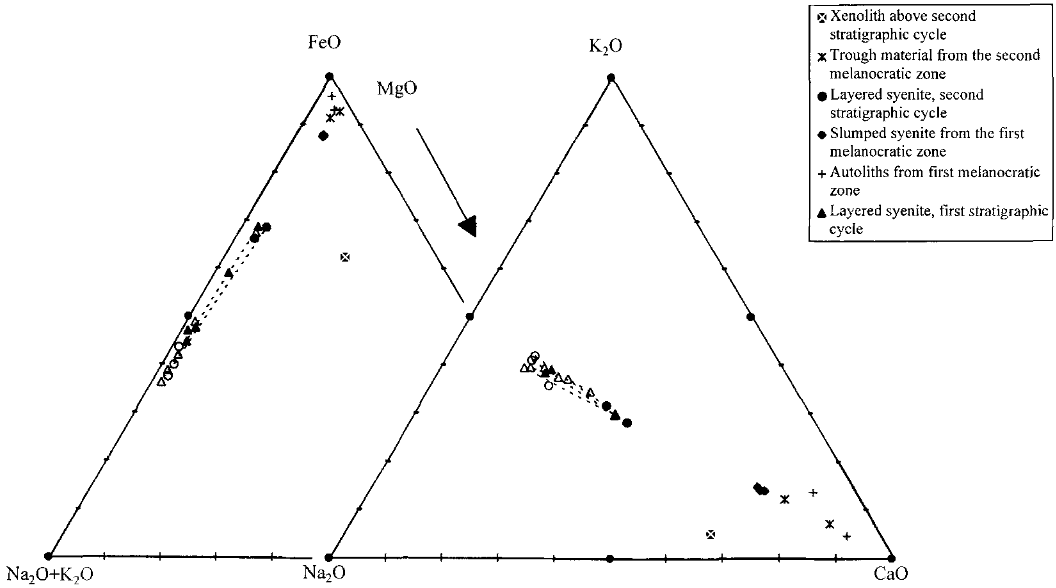

FIG. 3. Plots of Na_2O+K_2O:FeO:MgO and Na_2O:K_2O:CaO for whole-rock analyses from the Nunarssuit layered syenite. Samples from the base and top of individual layers are joined by a dashed line, samples from melanocratic bases of layers are solid, those from the leucocratic portions are open.

the slumps in Fig. 2*b* are at least 5 m deep) implies a substantial thickness of unconsolidated crystals at the base of the magma chamber.

It is improbable that the crossed layers (Fig. 2*e*) could be generated by deposition. Even if one of the layers was generated by deposition of crystals onto the chamber floor, the other must have been produced after the crystal pile had been deposited. The microrhythmic layering (Fig. 2*f*) occurs on an isolated outcrop. Layering on nearby rock faces, stratigraphically above, below and along strike is on the scale of tens of centimetres but the relation between the microrhythmic layering and the coarser layering is obscure due to discontinuous outcrop. There is a general consensus in the literature that inch-scale layering is generated by an *in situ* process (McBirney and Noyes, 1979; Boudreau, 1987).

Stratigraphy

The detailed stratigraphy of the layered zone of SW Nunarssuit is described from the base up. All thicknesses are stratigraphic thicknesses unless otherwise stated. Two basic stratigraphic cycles of layering have been recognized, in which faint layering becomes more intense up to a thick melanocratic zone. The thick melanocratic zones are characterized not only by their high colour index but also the concentration of slumps and breccias which occur in their vicinity. Diffuse, relatively regularly spaced, modal layering is also present above the second stratigraphic cycle. Gradually this layering becomes irregularly spaced and episodic and may be equivalent to the middle and upper layered zones as described by Harry and Pulvertaft (1963, their Fig. 16).

First cycle

The first cycle was assumed to start in the unlayered syenite observed along the west coast in the study area. Extrapolating from the map of P. Greenwood (pers comm.) the exposed thickness of this unlayered syenite is *c.* 500 m. Above this unlayered syenite modal layering begins to be observed, initially as poorly defined, irregularly spaced layers that become more regularly spaced and more distinct up section, with the colour index of the melanocratic bases increasing from *c.* 20% to 25%. Several large layered autoliths were observed, the orientation of the layering in the autoliths being different in each case. After a stratigraphic thickness of *c.* 110 m the layer spacing becomes relatively regular. Stacks of troughs occur (Upton *et al.*, 1996). The troughs contain melanocratic syenite that shows normal modal-grading with a colour index of *c.* 70% at the trough bases to a colour index of *c.* 50%, at the top. The troughs are up to several metres wide and 70 cm deep, and occur in approximately aligned vertical stacks which are continuous for stratigraphic thicknesses greater than 30 m. The troughs do not appear to disturb the surrounding modal rhythmic layering. It is not possible to determine the plunge of the trough axes as the troughs are exposed on smooth, flat rock surfaces. Small-scale unconformities between layers are seen. After about 60 m of this more regular layering a slumped melanocratic layer (colour index *c.* 60%), which is about 40 cm thick is observed. This layer marks the transition from regular modal layering to thicker, more melanocratic layers and also a higher concentration of slumps, breccias and autoliths. The colour index of the melanocratic material varies between 45 and 80 %. The melanocratic layers vary on the scale of 1 to 50 cm in both thickness and spacing along strike; most of the layers show normal grading. Feldspars sometimes occur as oikocrysts enclosing clinopyroxene in the very melanocratic parts of the layers. The base of this melanocratic zone is very undulatory due to folding and slumping and consequently the thickness of the zone varies between about 1 m and 5 m along strike in the area studied.

Second cycle

A similar cycle is seen stratigraphically above the first. The major differences are the thickness of the cycle and the occurrence of what was termed 'zebra-layering' in the zone of regular, distinct layering.

The cycle is stratigraphically thinner, 21 m as opposed to 176 m. In this cycle the faint irregular diffuse modal layering is present over a thickness of *c.* 10 m before becoming regular and more intense. This regular and intense layering is present for a further 10 m before a second melanocratic zone, this time 1 m thick, is encountered.

In places the sharply defined, regularly spaced, normally-graded layers consist of three separate sub-layers: (*a*) a *c.* 4 cm thick melanocratic base. This grades rapidly, over a thickness of about 1 cm, into (*b*) *c.* 11 cm thick normal syenite which is overlain in turn by (*c*) *c.* 4 cm of white syenite containing feldspars that are whiter than those in the normal syenite. The white layer has positive relief relative to the rock surfaces it is observed on. This layering is referred to as 'zebra-layering' due to the marked colour contrasts between the melanocratic and leucocratic portions of individual layers.

Layering above the second cycle

Layering above the second thick melanocratic zone is initially diffuse but regularly spaced. Up section, the layering becomes increasingly faint over a thickness of several hundred metres and ultimately the rocks appear wholly unlayered. Above this, diffuse layering occurs at irregular intervals. About 10m up from the level where layering is no longer visible, a layer of melanocratic syenite, melanocratic syenite autoliths and metabasite xenoliths occurs. This xenolith layer is probably the southern continuation of the Mercurius Havn–Kap Desolation xenolith zone reported by Harry and Pulvertaft (1963). If this is the case then the underlying syenite described previously is probably equivalent to the 'middle layered zone' of Harry and Pulvertaft (1963) and one of the occurrences of diffuse irregular layering is probably equivalent to their 'upper layered zone'.

Discussion of the stratigraphy

The tops of the two stratigraphic cycles are marked by a high concentration of major slump features and trough structures. Samples from the melanocratic zones are more mafic than underlying and overlying samples (Fig. 3). It is thought that this material represents side-wall cumulates which formed during the initial stages of the crystallization of the syenitic magma. Assuming that the slumps, troughs and breccias form in a fashion analogous to the sedimentary features which they resemble, this is good evidence that each stratigraphic cycle was terminated by an event which disrupted the magma chamber (such as eruption of the magma chamber, replenishment of the chamber with new magma, or earthquakes, which caused primitive side-wall cumulates to detach from the chamber sides and fall to the chamber floor) and which also rehomogenized the magma, resetting the layer producing mechanism. The failure of a complete cycle to develop above the second melanocratic zone implies that conditions were altered by a greater extent than at the end of the first cycle. The presence of a xenolith horizon above the second melanocratic zone indicates a change in the geometry of the magma chamber which may have been significant.

The increase in modal contrast between the melanocratic base and overlying leucocratic portion of each modal layer up section is not readily understood. Harris and Grantham (1993) report an increase in the bulk compositional difference between melanocratic and overlying leucocratic layers with increasing stratigraphic height in the layered zone of the Straumsvola nepheline syenite complex. The modal layering is expressed as concentrations of nepheline, aegirine-augite, biotite and amphibole in the melanocratic layers relative to alkali feldspar. They suggested that the modal layering is due to oscillatory nucleation with the structurally simple mafic phases crystallising first and then, when the magma is depleted in components present in the mafic phases, the structurally more complex alkali feldspar beginning to crystallize. Harris and Grantham (1993) tentatively suggested that the concentration of volatiles in the magma gradually built up as crystallization proceeded. This effect was superimposed on the oscillatory crystallization. The build up of volatiles suppressed feldspar nucleation further so that as crystallization proceeded less feldspar crystallized during the formation of the melanocratic layers. Such a mechanism would seem to be equally applicable to the Nunarssuit layering. If the thick melanocratic zones are produced by eruptions/earthquakes, the magma chamber would be greatly disturbed and possibly volatiles would escape from the chamber thereby 'resetting' volatile concentration so that the next cycle could begin. This model relies on the magma chamber being stratified which it probably was (see below) and assumes that the layers were formed essentially *in situ*. Although the layers and other structures observed resemble sedimentary structures, they may have been formed by the redistribution of crystals after the crystals had grown at the base of the magma chamber. It may be possible to test this hypothesis by determining the volatile content of fluid inclusions in primary cumulus phasees through the stratigraphy. All the volatile-bearing phases present (amphibole, biotite and apaptite) are either post-cumulus in origin or have had their chemistry modified by post-cumulus fluids, probably at low (<450°C) temperatures (see Hodson, 1997). Unfortunately, therefore it is not possible to look at the composition of these minerals to determine changes in volatile content of the magma during crystallization.

An alternative, physical hypothesis can be suggested to explain the increase in layering intensity. If the layers are the deposits of density currents, then it is possible that the increase in modal contrast is due to the sorting efficiency of the density currents. The sorting efficiency of density currents is most efficient closest to their source. Thus the high contrast in colour index between the bases and tops of layers could reflect high sorting efficiency close to the source of density currents, i.e. dense, mafic phases rapidly separated from less dense felsic phases, whilst the low contrast in colour index between the bases and tops of layers could reflect deposition from a density current far from its source once a high proportion of the dense phases had been deposited. Thus, moving vertically up through a stratigraphic cycle may be the same as moving laterally closer to the source of the density currents producing the layers. Such a hypothesis is not incompatible with the idea of a progressive increase in the concentration of volatiles. The buildup of volatiles would reduce viscosity, thereby reducing resistance to sorting in density currents so that the sorting efficiency of the currents would increase, i.e. the dense mafic, and less dense felsic minerals would be separated more rapidly and the contrast between the bases and tops of layers would increase. Further field work would be necessary to determine whether the intensity of layers altered along dip.

Both of the above hypotheses have to explain the inverse cryptic layering which is exhibited by the layered syenite and which is discussed below.

Petrography

The petrography of the Nunarssuit syenite is described in detail elsewhere (Hodson, 1997; Parsons and Butterfield, 1981; Harry and Pulvertaft, 1963) and is therefore only very briefly described here. The syenites are silica-saturated; alkali feldspar is the dominant mineral; mafic phases occur in higher concentrations at the bases of individual layers relative to the upper portions. The obvious cumulus phases are the sub- to euhedral clinopyroxene (ferro-salite/hedenbergite), olivine ($Fo_{2-10}Fa_{98-90}$) and apatite crystals. Opaque oxides and sulphides have a somewhat ambiguous mode of occurrence, commonly occurring as irregular rounded grains mantling olivines and clinopyroxenes but also occurring as isolated crystals mantled by biotite.

The classification of the alkali feldspar ($Or_{30-50}Ab_{50-70}An_{0-1.5}$) as cumulus or intercumulus is less obvious. As is usual in alkali feldspar no visible zoning of the grains is preserved and it is not possible to determine how much intercumulus growth occurred. In the case of the melanocratic rocks the feldspars commonly have irregular shapes and mantle other grains. It appears that the feldspars continued to crystallize after the mafic phases and apatite. In the case of the leucocratic syenite, feldspar is interpreted to be a cumulus phase.

Biotite (annite) and amphibole (barkevikite) appear to be largely subsolidus in origin (Hodson, 1997). Amphibole occurs predominantly as irregular patches within pyroxene grains and appears to be replacing it. However amphibole is also present, though rarely, as pyroxene-free, angular crystals which appear to have formed interstitially between feldspar crystals; this amphibole appears to be postcumulus. Biotite occurs as both aggregates of minute crystals forming fringes on magnetite and ilmenite, and as angular anhedral crystals. Crystals in the leucocratic facies are more altered than those in the melanocratic facies. This is due to more subsolidus modification occurring in the former (Hodson, 1997).

No mineral alignment is seen in the layered zone except in the two melanocratic units above and below slumps and autoliths. This alignment is probably due to either compaction or flow due to shearing in the crystal mush. Apart from this alignment there is no evidence that the cumulus pile underwent any compaction during solidification (Hodson, 1997).

Grain size variations

Variation in grain size with stratigraphic height, and across individual layers, was assessed qualitatively by comparing the grain size of crystals as observed in 210 mm × 297 mm photographs of 40 mm × 25 mm thin sections. The majority of clinopyroxene and olivine grains are sub- to euhedral and it was assumed that little or no adcumulus growth had occurred on these grains. No attempt was made to determine the dimensions of the feldspar crystals since the irregular grain shapes now present indicate that substantial postcumulus growth has occurred. No regular zoning is preserved so it is impossible to determine the original feldspar outline.

No systematic grain size variation for clinopyroxene or olivine is present in melanocratic samples nor is there any systematic grain size variation for clinopyroxene or olivine present between melanocratic and leucocratic samples. The clinopyroxenes have dimensions of roughly 0.5 × 0.8 × 1.0 mm and olivines 0.5 × 0.7 × 1.3 mm.

In recent years the theory of crystal size distribution (CSD) has received much attention through its application to igneous and metamorphic rocks (Marsh, 1988; Cashman and Marsh, 1988; Cashman and Ferry, 1988). The construction of CSD plots indicates whether the grain size distribution of the crystal population under consideration has been modified subsequent to crystallization. Recently CSD theory has been used (Waters and Boudreau, 1997) to show that the initial crystal size distribution of chromite grains in a chromite layer from the Stillwater complex were modified during an ageing event and that the chromite grains need not have accumulated by crystal settling. A preliminary application of CSD theory to olivines and pyroxene from the bases of layers from the layered syenite of Nunarssuit yields curves indicating that, like the chromites in Stillwater, the initial grain size distribution of olivines and pyroxenes has been modified (Fig. 4). An unmodified CSD plot should have a negative, log-linear trend. CSD plots indicating loss of fine grained material, for example due to Ostwald ripening, should have a positive slope at small grain sizes producing a bell shaped plot (as is seen in one of the olivine curves in Fig. 4*b*). The CSD plots produced from this study all appeared to show an increase in gradient at coarse grain sizes. Such plots may be interpreted as indicating depletion of the coarse grain fraction relative to an unmodified CSD. One possible explanation for such distributions is that the layers may have been produced by deposition from density currents, the coarsest grains having already been deposited closer to the source of the currents.

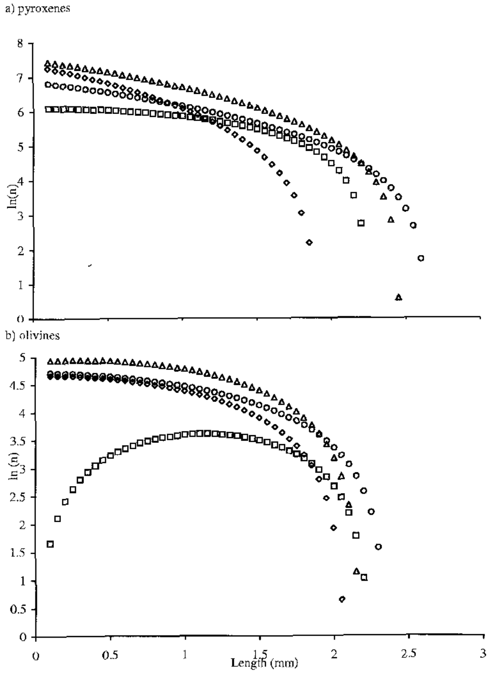

FIG. 4. Examples of CSD plots generated for (*a*) pyroxenes and (*b*) olivines from the bases of layers from the Nunarssuit layered syenite. Note all plots show an increase in gradient towards coarse grain sizes which may indicate a relative depletion in coarse grains. One olivine plot has a positive gradient at low grain sizes indicating depletion in small grain grains, possibly due to Ostwald ripening.

Crystal settling

In the Skaergård intrusion one of the major arguments against crystal settling being responsible for the modal rhythmic layering present is that plagioclase, a cumulus phase, is less dense than the probable parental magma of the layered series would have been, and should therefore have floated (McBirney and Noyes, 1979). Syenites, and the magmas from which they crystallize, have different physical properties from the basic magmas which are usually the subject of investigations into igneous layering and so it is worth carrying out calculations investigating the potential for crystal settling to occur.

Estimates of magma composition, T, P, water content, viscosity and density

In the absence of an exposed chilled margin or cogenetic dykes with chilled margins the composition of the syenitic magma (P1 in Table 1) from which the layers crystallized was taken to be the same as a trachytic dyke (no. 5 in Table 1 of Upton and Fitton, 1985) from the Tugtutôq-Ilímaussaq dyke swarm. This dyke has a phenocryst assemblage similar to the cumulus assemblage of the Nunarssuit syenites.

TABLE 1. Chemical analysis of potential Nunarssuit syenite parent magma, P1 (from Upton and Fitton, 1985)

	P1
SiO_2	59.64
Al_2O_3	15.14
Fe_2O_3	8.9
MgO	0.72
CaO	2.42
Na_2O	5.26
K_2O	5.73
TiO_2	1.13
MnO	0.2
P_2O_5	0.3
Total	99.43

Geothermometers give a range of temperatures for the crystallization of different phases in the Nunarssuit syenite (Table 2). The Nunarssuit syenite is compositionally similar to the Kûngnât and Klokken syenite. Upton (1960) estimated that the Kûngnât magmas were intruded at above 900°C on the basis of mineral compositions whilst McDowell and Wyllie (1971) concluded that the Kûngnât syenite crystallized above 800°C on the basis of experimental work. Parsons (1981) concluded that the Klokken syenites crystallized between 830 and 930°C. On the basis of this, a temperature of 850°C was used in calculations which required the temperature of the syenitic magma as an input parameter. No suitable geobarometers exist that could be applied to the Nunarssuit syenite. Xenoliths of supracrustal rock are present in the Nunarssuit syenite. The maximum uneroded thickness of supracrustal rocks preserved in the Gardar is 3 km (Parsons, 1981). To contain supracrustal xenoliths the magma must have been intruded to a minimum depth of 3 km so a pressure of 1 kbar has been used in equations. It is not known what the water content of the parent magma of the Nunarssuit syenites was but it is likely to have been less than 5% since at this level amphibole would have replaced pyroxene as a primary crystallising phase and the syenitic magma would have been water saturated for which there is no evidence.

Table 3 documents variations in density and viscosity in magma of composition P1 with varying water contents at a temperature of 850°C. Table 4 gives the densities (from Deer *et al.,* 1966) of the various cumulus phases at a temperature of 850°C.

Settling and convective velocities

Given that all the cumulus phases are denser than the magma the crystals could have settled if the magma was stagnant. Marsh and Maxey (1985) provide equations for peak convective velocity in the body of the magma chamber (their equation (60)). Table 5 shows minimum and maximum calculated peak convective velocities, corresponding to anhydrous P1 magma at 750°C and P1 magma containing 5% H_2O at 950°C respectively for convecting layers of 10 000 cm and 1 cm, together with settling velocities for ferrosalite/hedenbergite, fayalite and alkali feldspar calculated using Stokes Law. The convective velocities are, in all cases greater than settling velocities calculated using Stokes Law and assuming spherical grain shapes. Taking grain shape into account using the method of McNown and Malaika (1950) and also the Bagnold effect (Wadsworth, 1973) results in even lower settling velocities. Clearly the cumulus phases could not have settled through the body of the magma chamber. However, convective velocity falls to zero in boundary layers and so crystals could have settled in the boundary layer at the base of the magma chamber. It is also possible that crystal-

TABLE 2. Thermometers applied to cumulus phases from the Nunarssuit syenite

Thermometer	Crystallization temperature	Reference
Feldspar	>850°C	Nekvasil, 1992
Pyroxene stability	< 965°C	Deer *et al.*, 1966
Pyroxene-olivine	650–900°C	Kawasaki and Ito, 1993
Opaque oxides	600–750°C	Andersen and Lindsley, 1988

TABLE 3. Calculated values of density (g/cm^3) and viscosity (poise) for magma of composition P1 and varying water contents at 850°C

% water	Density$^+$	Viscosity$^{\#}$
0	2.5	7960481
1	2.5	1355933
2	2.5	299539
3	2.5	80822
4	2.5	26108
5	2.6	9701

$^+$ calculated following the method of Shaw (1972)
$^{\#}$ calculated after the method of Bottinga *et al.* (1982)

TABLE 4. Densities and fractionation densities of cumulus minerals from the Nunarssuit layered syenite. Densities expressed as g/cm^3

Mineral	Density	Fractionation density
Feldspar	2.6	2.33
Ferroaugite	3.5	3.13
Fayalite	4.4	6.13
Apatite	3.2	6.53
Ilmenite	4.7	5.06
Magnetite	5.2	4.8

liquid packages could have sunk though the magma to the bottom of the chamber. Also Marsh (1989, 1991) has suggested that convection may be weak in magma chambers after an initial start-up phase (see below).

An application of two recent layering models

Two recent models which apply to the formation of igneous layering yield conflicting results as to whether crystal settling would occur or not. In the model of Sparks *et al.* (1993) nucleation is assumed to occur heterogeneously within the body of the magma chamber. Settling occurs in stagnant boundary layers but convection keeps the majority of crystals suspended in the body of the chamber until a critical concentration of crystals is reached. When this concentration is reached, convection is damped and the crystals settle out forming a layer at the bottom of the chamber. Sparks *et al.* derived an equation for determining a critical viscosity, which varies for different minerals, above which crystal settling could not occur. Figure 5 illustrates results obtained applying Sparks' equation to magma of composition P1 at a temperature of 850°C and with varying water content. Data points represent the critical viscosity for the different phases whilst the horizontal lines represent the viscosity of P1 with differing water contents. Thus the model of Sparks *et al.* (1993) predicts that settling can occur if the data points plot below the horizontal lines. Results for calculations for anhydrous P1 have long dashed lines, P1 with 3% H_2O have short dashed lines and

TABLE 5. Convective velocities (calculated from equation (60), Marsh and Maxey, 1985) and settling velocities in cms^{-1}

Minimum convective velocity*	3.78×10^{-5}
Maximum convective velocity$^{\#}$	4168
Settling velocity$^{@}$	
Ferro-salite/hedenbergite	4.32×10^{-6}
Fayalite	8.89×10^{-6}
Alkali feldspar	6.33×10^{-7}

* for 750°C, 0% H_2O, convecting thickness of 10 000 cm
$^{\#}$ for 950°C, convecting thickness of 1 cm 5% H_2O,
$^{@}$ Stokes law settling rates in P1 at 950°C, 5% H_2O, i.e. maximum settling velocities Pyroxene crystals 0.5 × 0.8 × 1.0 mm, olivine 0.5 × 0.7 × 1.3 mm and feldspar 1.0 × 5.0 × 5.0 mm

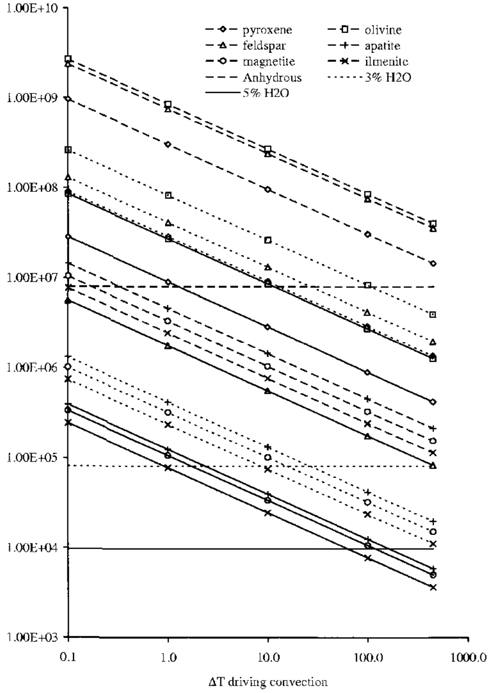

FIG. 5. Plot of critical viscosities (after Sparks *et al.*, 1993) calculated for the cumulus phases of the Nunarssuit layered syenite for magma of composition P1 at 850°C with varying water content and temperature driving convection. Magma density and viscosity and mineral densities are given in Tables 3 and 4 respectively. Coefficient of thermal expansion = 5 × 10^{-3} K^{-1} and thermal diffusivity = 5 × 10^{-3} cm^2s^{-1} (both from Bagdassarov and Fradkov, 1993). Particle dimensions used were feldspar: 1.0 × 5.0 × 5.0 mm, pyroxene 0.5 × 0.8 × 1.0 mm, olivine 0.5 × 0.7 × 1.3 mm, apatite 0.1 × 0.1 × 1.0 mm, ilmenite 0.1 × 0.1 × 0.1 mm and magnetite 0.1 × 0.1 × 0.1 mm.

5% H_2O have continuous lines. Several points should be noted. Both the temperature difference driving convection and the water content of the magma are crucial controls on the calculated value of the critical viscosity. As the temperature difference driving convection falls settling is less likely to occur as this causes the critical viscosity to rise. Somewhat counter intuitively the model predicts that as the water content of the magma increases settling becomes less likely, this is because the critical viscosity falls at a greater rate than the actual viscosity. Under the conditions of crystallization estimated for the Nunarssuit magma chamber the model of Sparks *et al.* predicts that the dominant cumulus phases pyroxene, olivine and feldspar will not settle.

A second recent model (Hort *et al.*, 1993) deals with oscillating nucleation and crystallization of two solid phases in the body of a magma chamber, crystal settling being responsible for removing the phases from the site of crystallization. The model is limited in that it is only concerned with two solid phases, a fact acknowledged by the authors. However Hort *et al.* present simple approximate equations which allow a prediction to be made as to whether layers will form or not on the basis of magma properties and chamber size. Settling can occur if Se, the settling number is greater than the critical settling number, Se_{crit}. Table 6 shows calculated values for Se and Se_{crit} for magma of composition P1 with varying water content at 850°C. Regardless of the water content chosen for the magma, from 0% to the saturation concentration of 5%, Se_{crit} is always greater than the Se.

Two different models produce different predictions as to whether layering could form in the Nunarssuit syenite due to crystal settling. Using mathematics it is possible to predict the formation

TABLE 6. Values of Av, Se and Se_{crit} for magma of composition P1 at 850°C and varying water contents. Densities and viscosities used are given in Tables 3 and 4, all shape factors were set to 1. Other values used are thermal diffusivity = 5 × 10^{-3} cm^2s^{-1} and coefficient of thermal expansion = 5 × 10^{-3} K^{-1} from Bagdassarov and Fradkov (1993) and I_m = 50000 m^3s^{-1} and U_m = 10^{-8} ms^{-1} from Hort *et al.* (1993). H is estimated at 10^3 m (though Se > Se_{crit} for all values of H > 100 m)

% H_2O	Av	Se	Se_{crit}
0	8 × 10^{29}	9.04 × 10^6	1.28 × 10^5
3	8 × 10^{29}	6.46 × 10^7	1.28 × 10^5
5	8 × 10^{29}	1.59 × 10^8	1.28 × 10^5

of layers in a variety of ways. Whilst this allows some aspects of hypotheses to be tested it does not show how layers in the rocks formed, nor does it help to explain the occurrence of many layered structures.

Magma chamber zonation

Sparks and Huppert (1984) defined "fractionation density" as "the ratio of the gram formula weight to molar volume of the chemical components in the liquid phase that are being removed by fractional crystallization". If the fractional density of a mineral phase is greater than the magma from which it crystallizes the residual magma will be less dense than the original magma. Under such situations compositional convection may occur leading to the formation of a compositionally zoned magma chamber (Turner and Campbell, 1986). Apart from feldspar, the fractionation densities of the cumulus phases of the Nunarssuit syenite are greater than the parental magma density (Table 4). The net fractionation density of the primary crystallising assemblage would have been greater than the density of the parent magma and therefore the Nunarssuit magma chamber could have become stratified.

Whilst it is not possible to determine the precise nature of the magma zonation it is likely that temperature decreased upwards to the top of the chamber due to heat loss through the chamber roof and that the magma became more ferroan towards the top of the chamber due to the density driven rise of residual components of syenitic magma after the crystallization of feldspar and mafic phases. Such an arrangement would be dynamically stable whilst the compositional density effect dominated over the thermal density effect.

It should be noted that the Rayleigh number of the magma indicates that the magma would have been convecting turbulently (Rayleigh number $> 10^5$, Cox *et al.*, 1979). If this is the case it seems likely that any compositional zoning which may potentially have developed in the magma chamber would have been disrupted. However Marsh (1989, 1991) has suggested that convection is weak in sheet-like magma chambers after an initial start-up phase, though this work has not received universal acceptance (Huppert and Turner, 1991). The geometry of the Nunarssuit magma chamber is not known, not least because some of the Nunarssuit syenite is below the Davis Strait. It has been shown that the Nunarssuit syenite consists of five units (Emeleus and Upton, 1976), the configuration of which indicates emplacement as a series of pulses. It is the outer most arcuate unit of syenite which exhibits the layering phenomenon under discussion here and it is entirely conceivable that this unit was sheet-like when intruded. Whilst acknowledging that this is by no means certain, we assume that the Nunarssuit syenite magma chamber was sheet-like, that convection was gentle and that the magma was compositionally zoned in order to explain the inverse cryptic variation seen in the layered series (see below).

Cryptic variation

Aspects of the chemistry of the Nunarssuit layered syenites are discussed in Hodson (1997) and Parsons and Butterfield (1981). For the present paper the important point is that the layered series is inversely cryptically layered with a slight, but statistically significant, increase in the ratio $Mg/(Mg + Fe_{total})$ with stratigraphic height. This inverse cryptic layering is seen in both whole rock compositions (Fig. 6*a*) and the different mafic phases present in the syenites (Fig. 6*b–e*).

Reverse cryptic variation has been reported at the bases of a number of layered intrusions. Raedeke and McCallum (1984) suggested that the trend of increasing $Mg/(Mg+Fe_{total})$ at the base of the Stillwater complex was due to equilibration between the cumulus phases and trapped liquid. Initially the liquid was of fairly constant composition and was more ferroan than the cumulus phases. Re-equilibration resulted in Fe enrichment of the cumulus phases. Raedeke and McCallum postulated that initial porosity of the crystal pile decreased as crystallization proceeded so that the volume of liquid available for re-equilibration decreased. Thus cumulus phases became less ferroan up section due to the decrease in postcumulus re-equilibration.

Whilst there is evidence for re-equilibration of cumulus phases with intercumulus melt in the Nunarssuit syenites (Hodson, 1997; Parsons and Butterfield, 1981) there is no evidence that porosity of the cumulus pile decreased up section or that the degree of re-equilibration decreased up section and so the hypothesis of Raedeke and McCallum seems inapplicable.

Wilson *et al.* (1987) postulated crystallization of a vertically stratified magma against an inclined floor to explain the reversed cryptic

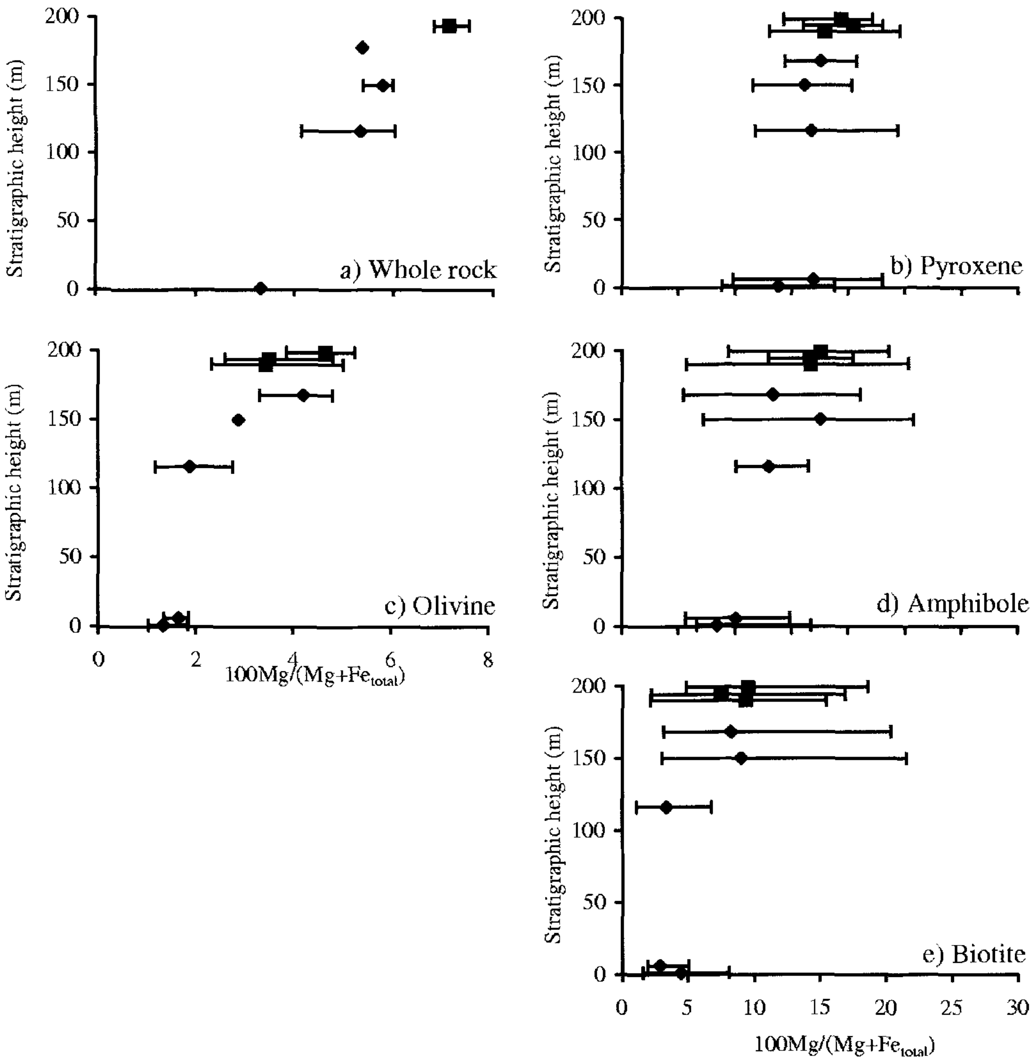

Fig. 6. Variation of 100Mg/(Mg+Fe$_{total}$) with stratigraphic height in leucocratic syenites from the Nunarssuit layered syenite for: (*a*) whole-rocks; (*b*) clinopyroxenes; (*c*) olivines; (*d*) amphiboles; (*e*) biotites. Closed symbols are average values for all samples analysed from that stratigraphic level. Horizontal bars show minimum and maximum values. Data for melanocratic samples shows similar trends. Diamonds indicate samples from the first stratigraphic cycle, squares from the second.

layering observed in the Fongen–Hyllingen intrusion of Norway. In this model the stratified magma becomes more evolved upwards and modal layering is produced by oscillatory nucleation against the sloping floor of the chamber. Mineral compositions within the modal layers are governed by the chemistry of the layer of magma from which the crystals formed. Thus modal and cryptic layering are discordant; the modal layering is parallel to the sloping chamber floor whilst the compositional layering is horizontal. Primitive, dense magma is intruded into the bottom of the chamber and the magma layers are pushed upwards. In this way the modal layers come into contact with progressively more primitive (magnesian) magma.

It is possible that the reverse cryptic layering observed in the Nunarssuit syenite was produced by the repeated injection of small volumes of magma at the base of the chamber as in the model of Wilson *et al.* (1987) though a large number of consecutive magma pulses would be required if each modal layer was the product of crystallization from a new influx of magma.

Wilson's model to explain inverse cryptic layering may be combined with that of Harris and Grantham (1993) to explain the increased modal contrast between layers up section. Harris and Grantham envisage consecutive crystallization of the lower-most magma layer; volatiles which are not incorporated into the crystallising assemblage move into the overlying magma layer and therefore increase in concentration. This is in contrast to the model of Wilson where individual magma layers are gradually pushed up the magma chamber by the repeated injection of magma below them. If volatiles built up in individual magma layers the influence they had on the modal composition of the crystallising assemblage would be parallel to the chemical zoning as opposed to the modal layering and the visual effect would be the generation of layers where the modal contrast between bases and tops of layers became more intense up dip.

A new mechanism for generating the inverse cryptic variation which does not involve *in situ* layer formation is shown in Fig. 7. This mechanism is compatible with the physical hypothesis put forward to explain the increase in modal contrast between the bases and tops of layers. This mechanism assumes that the magma chamber is compositionally zoned with successive over-lying magma layers becoming more ferroan (see above). As the upper magma layer cools against the roof of the chamber and begins to crystallize its net density increases and it begins to sink in a fashion similar to that envisaged by Wager and Brown (1968). The package of crystals and liquid reaches the chamber floor and flows along the inclined floor as a density current from

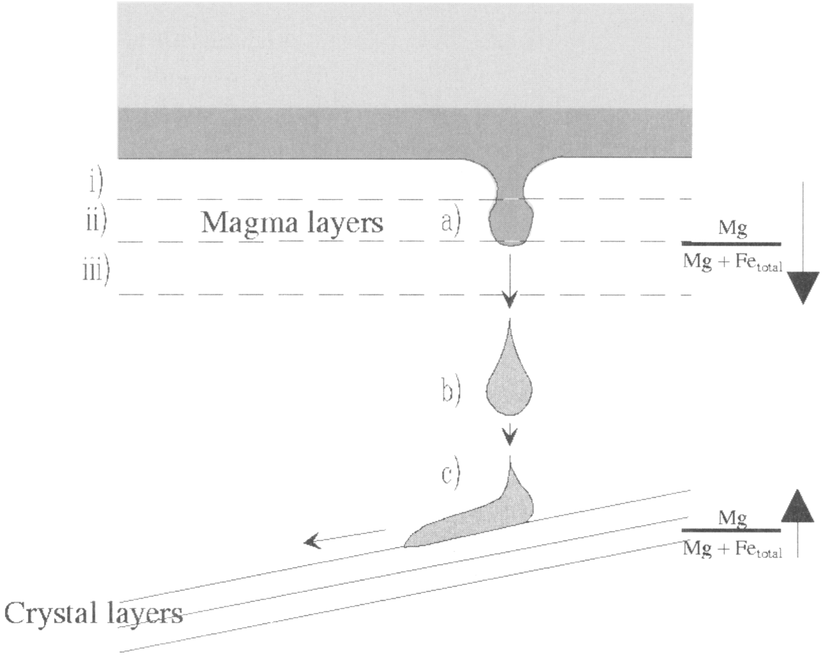

FIG. 7. Hypothesized mechanism for generating a reversed cryptically layered succession in a compositionally zoned magma chamber. Crystallization occurs in the boundary layer under the roof of the chamber. The layer becomes unstable and sinks (*a–b*) through the compositionally zoned magma chamber. At the floor of the chamber (*c*) the packet of crystals and melt spreads out and flows as a density current depositing crystals. The process repeats itself with successive magma layers, of increasing Mg content, sinking and crystallising (i–iii etc.).

which crystals are deposited. It is assumed that the crystal-liquid package will sink to the bottom of the chamber by virtue of its momentum even if it reaches a level in the zoned magma where it is neutrally buoyant. The next layer of magma at the top of the chamber then sinks and the process repeats. Successive layers of crystallising magma are more magnesian (layers i, ii and then iii in Fig. 7) and the chemistry of the crystals in the layers produced at the base of the magma chamber reflects this. This hypothesis predicts that modal layering is concordant with the cryptic layering. Because the layering is produced by density currents, layers should become progressively more depleted in the coarse grain fraction as the density currents flow further from their source. Also layers should become more diffuse the further they are from the source of the current due to a decrease in sorting efficiency.

The concordance, or lack or concordance, between the modal and cryptic layering could be used to choose between the two hypotheses presented here to explain the cryptic layering. Further field work is therefore required before either of the two hypotheses may be adopted with confidence. However, initial CSD plots indicate that the layers are depleted in the coarsest grain fractions which counts in favour of the second hypothesis. It should be stressed that both hypotheses required layered magma chambers in which convection, of necessity, is not vigorous or is confined to individual layers.

Cryptic variation across individual layers

Within individual layers the mafic phases are more magnesian in the melanocratic bases of the layers compared with the top of the layers (Hodson, 1997). This trend was first reported by Parsons and Butterfield (1981) and is thought to represent a "trapped liquid shift" as described by Barnes (1986). Therefore it seems likely that for any given phase there was initially no systematic chemical variation across individual layers. Conrad and Naslund (1989) interpreted this as being indicative of an origin due to deposition from density or convection currents.

Synthesis

On the basis of the above evidence the preferred model for the formation of igneous layering within the Nunarssuit syenite is as follows. After injection of the syenitic magma, rapid crystallization occurred against the sidewalls of the chamber where the magma was in contact with country rock and was super-cooled. The side wall cumulates produced were melanocratic due to the lower nucleation barrier for the crystallization of structurally simple pyroxene and olivine crystals compared to the structurally more complex feldspars. After the formation of an insulating layer of crystals against the walls of the chamber the magma began to crystallize in the body of the chamber. Initially the majority of crystals were kept in suspension by the turbulently convecting magma but those in the boundary layer at the base of the magma chamber settled onto the chamber floor. The convective vigour of the magma decreased as crystals accumulated and grew on the chamber floor, evolved residual melt rose upwards due to its lower density compared to the surrounding magma. Thus the magma became compositionally stratified with magma becoming more evolved (ferroan) upwards. As the country rock heated up, cooling of the chamber became focused at the top of the chamber. Successive upper layers of magma began to crystallize, cooled, became unstable and sank to the chamber floor as a crystal-melt plume. On reaching the chamber floor the plumes flowed along the chamber floor as debris-flow like currents. Alternatively crystals may have accumulated as loosely consolidated piles below descending plumes or vertical boundary layers at the margins of the chamber. As the piles grew they ultimately became unstable and collapsed, generating debris-flow currents. In either case the coarsest grains would be deposited closest to the source of the currents and the degree of sorting and therefore layer intensity would decrease away from the source of the current down dip. Since successively crystallising layers were more magnesian, the crystals which were carried to the bottom of the chamber were also successively more magnesian resulting in a layered succession which is inversely cryptically layered. After the formation of any single layer, the crystals in that layer re-equilibrated with the interstitial melt, the base becoming more ferroan than the top.

An alternative method for the formation of the layers and the inverse cryptic layering is that layers formed *in situ* against the sloping magma chamber floor by a process of oscillatory nucleation in successive layers of primitive magma introduced into the bottom of the chamber. In each magma layer the relatively simple structured pyroxenes and olivines nucleated and grew before the structurally more complex feldspars. When the magma was depleted in pyroxene and olivine components feldspar began to crystallize during which interval the pyroxene and olivine components built up again. As crystallization proceeded the concentration of volatiles in the magma layers built up so that feldspar nucleation was increasingly inhibited during the formation of the melanocratic bases of the layers. This caused the contrast between the bases and tops of the layers to increase up dip.

Field work is required to differentiate between these two models, the former produces concordant modal and cryptic layering whilst the latter does not. The depletion of coarse grains of pyroxene and olivine from the bases of layers as demonstrated by CSD plots perhaps favours the former hypothesis. Both hypotheses rely on convection in the magma being gentle and not disrupting the hypothesized compositional zoning.

The cyclicity of the stratigraphy is probably related to periodic eruption and resetting of magma chamber conditions. The early formed sidewall cumulates were detached from the walls during these eruptions and sank to the base of the chamber either as autolithic blocks or as streams of slurry which eroded the crystal pile and formed trough structures, slumps and breccias. It is not known why a third cycle failed to develop or why layering fades up section. The proximity of the xenolith zone to the second melanocratic zone is perhaps significant, implying a change in chamber geometry, and possibly convective regime or magma zonation which altered magma chamber conditions so that they were not favourable towards layer production.

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References

Andersen, D.J. and Lindsley, D.H. (1988) Internally consistent solution models for Fe-Mg-Mn-Ti oxides: Fe-Ti oxides. *Amer. Mineral.*, **73** 714–26.

Anderson, J.G. (1974) *The geology of Al<ngorssuaq, Northern Nunarssuit complex, South Greenland.* Unpubl. PhD thesis, Univ. Aberdeen.

Bagdassarov, N. S. and Fradkov, A.S. (1993) Evolution of double diffusion convection in a felsic magma chamber. *J. Volc. Geotherm. Res.*, **54** 291–308.

Bak, P. and Chen, K. (1991) Self-organised criticality. *Scientific American*, **264**, 26–33.

Barnes, S.J. (1986) The effect of trapped liquid crystallisation on cumulus mineral composition in layered intrusions. *Contrib. Mineral. Petrol.*, **93**, 524–31.

Blaxland, A.B., Breemen, O. van, Emeleus, C.H. and Anderson, J.G. (1978) Age and origin of the major syenite centres of the Gardar: Rb–Sr studies. *Geol. Soc. Amer. Bull.*, **78**, 231–44.

Bottinga, Y., Weill, D.F., Richet, P. (1982) Density calculations for silicate liquids 1. Revised method for aluminosilicate compositions. *Geochim. Cosmochim. Acta*, **46**, 909–19.

Boudreau, A.E. (1987) Pattern formation during crystallisation and the formation of fine-scale layering. In: *Origins of Igneous Layering* (I. Parsons, ed.). NATO ASI Series C196, D. Reidel Publishing Company, Dordrecht, 453–71.

Butterfield, A.W. (1980) *Geology of the Western part of the Nunarssuit alkaline complex of south Greenland.* Unpubl. PhD thesis, Univ. Aberdeen.

Cashman, K.V. and Ferry, J.M. (1988) Crystal size distribution in rocks and the kinetics and dynamics of crystallisation III. Metamorphic crystallisation. *Contrib. Mineral. Petrol.*, **99**, 401–15.

Cashman, K.V. and Marsh, B.D. (1988) Crystal size distribution in rocks and the kinetics and dynamics of crystallisation II. Igneous crystallisation. *Contrib. Mineral. Petrol.*, **99**, 292–305.

Cawthorn, R.G. (1996) *Layered Intrusions.* Elsevier Science B.V. 531 pp.

Conrad, M.E. and Naslund, H.R. (1989) Modally-Graded Rhythmic Layering in the Skaergaard Intrusion. *J. Petrol.*, **30**, 251–69.

Cox, K.G., Bell, J.D. and Pankhurst, R.J. (1979) *The Interpretation of Igneous Rocks.* George Allen and Unwin, 450 pp.

Deer, W.A., Howie, R.A. and Zussman, J. (1966) *An Introduction to the Rock-Forming Minerals.* Longman 528 pp.

Emeleus, C.H. and Upton, B.G.J. (1976) The Gardar Period in southern Greenland. In: *The Geology of Greenland* (A. Escher and W.S. Watt, eds). Grønls. Geol. Unders., Copenhagen, 153–81.

Ferguson, J. and Pulvertaft, T.C.R. (1963) Contrasted styles of igneous layering in the Gardar province of South Greenland. *Spec. Pap. Mineral. Soc. Amer.*, **1**, 10–21.

Harris, C. and Grantham, G.H. (1993) Geology and petrogenesis of the Straumsvola nepheline syenite complex, Dronning Maud Land, Antarctica. *Geol. Mag.*, **130**, 513–32.

Harry, W.T. and Pulvertaft, T.C.R. (1963) The Nunarssuit intrusive complex, S Greenland. *Bull. Grønlands geol. Unders.*, **36.**

Hodson, M.E. (1994) Igneous layering in the syenites of Nunarssuit and West Kungnat, South Greenland. Unpubl PhD thesis, Univ. Edinburgh.

Hodson, M.E. (1997) Post-crystallisation modification of the Nunarssuit and West Kûngnât layered syenites, South Greenland. *Mineral. Mag.*, **61**, 467–83.

Hort, M., Marsh, B.D. and Spohn, T. (1993) An oscillatory nucleation model for igneous layering. *Contrib. Miner. Petrol.*, **114**, 425–40.

Huppert, H.E. and Turner, J.S. (1991) Comments on 'On convective style and vigor in sheet-like magma chambers' by Bruce Marsh. *J. Petrol.*, **32**, 851–4.

Irvine, T.N. (1987*a*) Processes involved in the formation and development of layered igneous rocks. Appendix II. In: *Origins of Igneous Layering* (I. Parsons, ed.). NATO ASI Series C196, D. Reidel Publishing Company, Dordrecht. 649–56.

Irvine, T.N. (1987*b*) Layering and related structures in the Duke Island and Skaergaard intrusion: similarities, differences and origins. In: *Origins of Igneous Layering* (I. Parsons, ed.). NATO ASI Series C196, D. Reidel Publishing Company, Dordrecht. 185–245.

Kawasaki, T. and Ito, E. (1993) Fe-Mg partitioning between olivine and Ca-rich clinopyroxene: Implications for Fe-Mg mixing properties of Ca-rich clinopyroxene. Technical report of ISEI SerA No **54**, 50 pp.

Marsh, B.D. (1988) Crystal size distribution in rocks and the kinetics and dynamics of crystallisation I: Theory. *Contrib. Mineral. Petrol.*, **99**, 277–91.

Marsh, B.D. (1989) On convective style and vigor in sheet-like magma chambers. *J. Pet.*, **30**, 479–530.

Marsh, B.D. (1991) Reply [to H.E. Huppert and J.S. Turner]. *J. Petrol.*, **32,** 855–60.

Marsh, B.D. and Maxey (1985) On the distribution and separation of crystals in a convecting magma. *J. Volc. Geoth. Res.*, **24**, 94–150.

McBirney, A.R. and Noyes, R.M. (1979) Crystallisation and layering of the Skaergaard Intrusion. *J. Petrol.*, **20**, 487–554.

McDowell, S.D. and Wyllie, P.J. (1971) Experimental studies of igneous rock series: The Kûngnât syenite complex of Southwest Greenland. *J. Geol.*, **79**, 173–94.

McNown, J.S. and Malaika, M. (1950) Effects of particle size on settling velocities at low Reynolds numbers. *Trans. AGU*, **31**, 74–82.

Nekvasil, H. (1992) Ternary feldspar crystallisation in high temperature felsic magma. *Amer. Mineral.*, **77**, 592–604.

Parsons, I. (1981) The Klokken gabbro-syenite complex, South Greenland: quantitative interpretation of mineral chemistry. *J. Pet.*, **22**, 233–60.

Parsons, I. (ed), (1987) *Origins of Igneous Layering.* NATO ASI Series C196, D. Reidel Publishing Company, Dordrecht, 666 pp.

Parsons, I. and Butterfield, A.W. (1981) Sedimentary features of Nunarssuit and Klokken syenites, S Greenland. *J. Geol. Soc. Lond.*, **138,** 289–306.

Raedeke, L.D. and McCallum, I.S. (1984) Investigations in the Stillwater Complex: Part II. Petrology and petrogenesis of the Ultramafic Series. *J. Pet.* **25** 395–420.

Shaw, H.R. (1972) Viscosities of magmatic silicate liquids: An empirical method of prediction. *Amer. J. Sci.*, **272,** 870–93.

Sparks, R.S.J. and Huppert, H.E. (1984) Density changes during the fractional crystallisation of basaltic magmas: fluid dynamic implications. *Contrib. Mineral. Petrol.*, **85**, 300–4.

Sparks, R.S.J., Huppert, H.E., Koyaguchi, T. and Hallworth, M.A. (1993) Origin of modal and rhythmic igneous layering by sedimentation in a convecting magma chamber. *Nature,* **361,** 246–9.

Turner, J.S. and Campbell, I.H. (1986) Convection and mixing in magma chambers. *Earth Science Reviews,* **23**, 255–352.

Tucker, M.E. (1981) *Sedimentary petrology: An introduction.* Blackwells scientific publications, 252 pp.

Upton, B.G.J. (1960) The alkaline igneous complex of Kûngnât Fjeld, South Greenland. *Grøn. Geol. Und. Rap.*, **123.**

Upton, B.G.J. (1974) The alkali province of SW Greenland. In: *The Alkaline Rocks* (H. Sørensen, ed.). Wiley, New York, 221–38.

Upton, B.G.J. and Emeleus, C.H. (1987) Mid-Proterozoic alkaline magmatism in S Greenland: The Gardar Province. In: *Alkaline Igneous Rocks* (J.G. Fitton, and B.G.J. Upton, eds). Geol. Soc. Spec. Publ., **30**, 449–71.

Upton, B.G.J. and Fitton, J.G. (1985) Gardar dykes north of the Igaliko syenite complex, S Greenland. *Grøn. Geol. Und. Rap.*, **127**.

Upton, B.G.J., Emeleus, C.H., Parsons, I. and Hodson, M.E. (1996) Layered alkali igneous rocks of the Gardar province, South Greenland. In: *Layered Intrusions* (R.G. Cawthorn, ed.). Elsevier Science B.V., 331–63.

Wadsworth, W.J. (1973) Magmatic sediments. *Minerals Sci. Eng.*, **5**, 25–35.

Wager, L.R. and Brown, G.M. (1968) *Layered Igneous Rocks.* Oliver and Boyd, Edinburgh, 588 pp.

Waters, C. and Boudreau, A.E. (1997) A reevaluation of crystal-size distributions in chromite cumulates. *Amer. Mineral.*, **81**, 1452–9.

Wilson, J.R., Menuge, J.F. and Pedersen, S. (1987) The southern part of the Fongen-Hyllingen layered mafic complex, Norway: Emplacement and crystallisation of compositionally stratified magma. In: *Origins of Igneous Layering* (I. Parsons, ed.). NATO ASI Series C196, D. Reidel Publishing Company, Dordrecht 145–84.

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