

Crystallization from stratified magmas in the Honningsvåg Intrusive Suite, northern Norway: a reappraisal

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Abstract

Wedge-shaped layers of ultramafic and mafic cumulates in Intrusion II of the Caledonian Honningsvåg Intrusive Suite suggest crystallization on an inclined magma chamber floor from a compositionally-zoned and density-stratified magma.

Cyclic unit 8 (140–100 m thick) consists of a distally-thinning olivine gabbro (denoted paoC) macrolayer overlain by a distally-thickening gabbronorite, pahC. New mineral data in four traverses across cyclic unit 8 show systematic compositional changes; the Mg# of the mafic phases decreases upwards through the unit and distally, both along the base and along the paoC/pahC interface.

A crystallization model based on an effectively continuously-zoned magma chamber with numerous, relatively thin, double-diffusive magma layers is proposed. Differential migration of horizontal isopleths (e.g. Mg# and a_{SiO_2}) in response to fractional crystallization and assimilation of country rock can explain the variations in the Mg# of the cumulates.

KEYWORDS: magma chamber, cumulates, double-diffusive convection, cyclic unit, Honningsvåg, Norway.

Introduction

MAGMA stratification and bottom crystallization (e.g. Campbell, 1978; McBirney and Noyes, 1979) has for almost two decades been the most acceptable alternative to crystal settling (Wager and Brown, 1968) during the formation of layered mafic and ultramafic cumulates. Crystallization models involving an inclined magma chamber floor generally assume a density-stratified magma column with horizontal layers bounded by double-diffusive interfaces (Irvine, 1981; Irvine *et al.*, 1983; Wilson and Larsen, 1985; Young *et al.*, 1988; Prendergast, 1991; Wilson, 1992). This concept is rooted in fluid dynamic experiments with aqueous solutions where

compelling evidence for double-diffusive convection exists (Turner and Campbell, 1986 and references therein).

The arrangement of wedge-shaped macrolayers in Intrusion II of the Honningsvåg Intrusive Suite (Fig. 1) has been regarded as an example of crystallization from double-diffusive magma layers along an inclined floor (Fig. 2) of a periodically-replenished magma chamber (Robins *et al.*, 1987). The present paper is the result of a recent investigation of cyclic units in the upper part of Intrusion II. Evidence for the intrusion of picritic sills into unconsolidated, first-stage cumulates, resulting in the formation of peridotite and olivine melagabbro sheets as a consequence of crystal-melt reactions, is

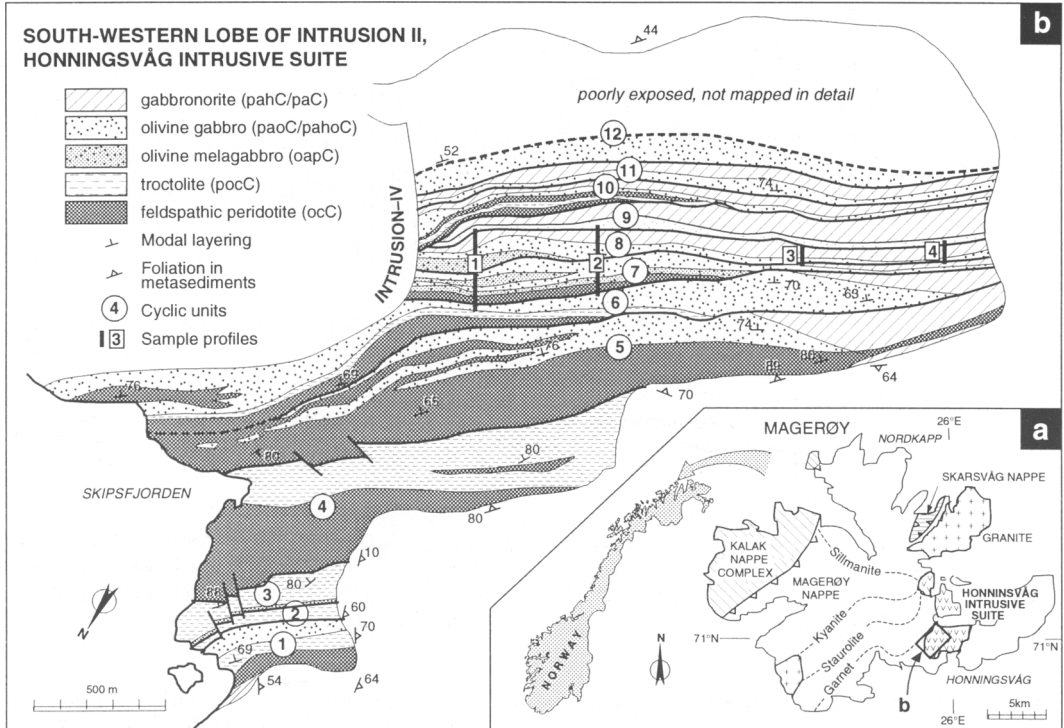


FIG. 1. (a). Map of Magerøy (Roberts and Andersen, 1985) showing location of b. (b). Simplified geological map of Intrusion II (modified after Robins *et al.*, 1987) showing the distribution of rock-types, cyclic units and sampled traverses. Rock names given in parantheses follow the cumulus terminology, which will be used in this study, where o = olivine, p = plagioclase, a = Ca-rich pyroxene, h = Ca-poor pyroxene, c = chromite, C = cumulate; cumulus minerals are listed in order of decreasing modal abundance. This study is restricted to that part of the four traverses crossing cyclic unit 8, whereas the companion paper (Tegner and Robins, 1996, this volume) deals mainly with peridotite and olivine melagabbro sheets in cyclic unit 7.

presented in a companion paper (Tegner and Robins, 1996, this volume).

Here we use field relations, petrography and mineral chemistry of the first-stage cumulates in cyclic unit 8 to argue that: (1) crystallization took place on an inclined floor in a replenished magma chamber; (2) magma addition was turbulent and magma mixing resulted in basal hybrids with an upwardly decreasing ratio of new to residual magma; (3) crystallization probably took place from an effectively continuously-zoned magma with numerous thin double-diffusive layers; and (4) some of the cumulates consist of mixtures of pre-existing plagioclases and other minerals which crystallized from the hybrid magma.

The Honningsvåg Intrusive Suite

The Honningsvåg Intrusive Suite is located on the island of Magerøy, northernmost Norway (71°N,

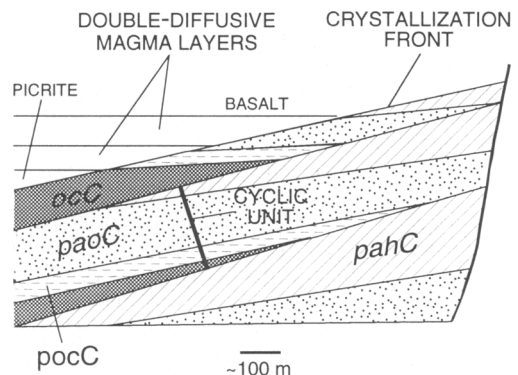


FIG. 2. Replenishment model showing how crystallization from large-scale double-diffusive magma layers along an inclined magma chamber floor leads to wedge-shaped macrolayers (Robins *et al.*, 1987). Modal layering is parallel to the crystallization front.

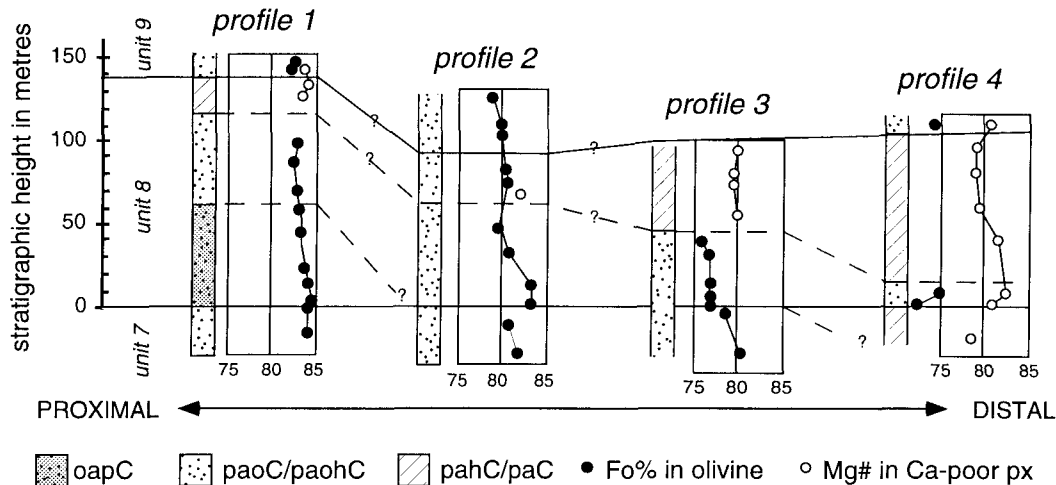


FIG. 3. Lateral correlation of macrolayers in profiles 1–4 of cyclic unit 8. The cryptic variation of average Fo% in olivine and average Mg# in Ca-poor pyroxene are shown to the right of the stratigraphic columns. Each point represents an average of 6–9 analyses in a thin section. 2σ deviations are $\sim 0.4\text{Fo}\%$ in olivine and $\sim 2.0\text{Mg}\#$ in Ca-poor pyroxene (Table 2), which is less than the size of the symbols used.

26°E , Fig. 1a). It is emplaced into folded turbidites of the Upper Allochthon of the Scandinavian Caledonides (Gee and Sturt, 1985).

Internally the intrusive rocks are little affected by the orogeny (Robins *et al.*, 1987) and there is no doubt that the architecture of the macrolayers described here is the result of magmatic processes. Graptolites of Middle Llandoveryan age (Krill *et al.*, 1993) are preserved in the contact metamorphic aureole, constraining the age of the intrusives to <420 Ma. The Honningsvåg Intrusive Suite exposes a cross-section of a body that extends >6 km beneath the surface (Robins *et al.*, 1987; Torsvik *et al.*, 1992). Detailed petrological investigations are few. Curry (1975), in a regional study, recognized four intrusive events (allivalite, gabbro, peridotite and dunite). Later, Robins *et al.* (1987) and Robins (1993) demonstrated that the intrusive suite consists of at least four layered mafic intrusions emplaced above one another as a consequence of the upward migration of successive magma chambers.

The south-western lobe of Intrusion II is probably one wing of a lopolith and provides excellent exposures of a ~ 2 km-thick sequence of cumulates (Fig. 1b). A complex sequence of wedge-shaped macrolayers has been subdivided into 12 cyclic units (average thickness ~ 166 m) by Robins *et al.* (1987). The ideal cyclic unit, from base to top, consists of peridotite (ocC), troctolite (pocC), olivine gabbro (paoC) and gabbronorite (pahC). Rock names are given using the cumulus terminology where o =

olivine, p = plagioclase, a = Ca-rich pyroxene, h = Ca-poor pyroxene, c = chromite, C = cumulate; cumulus minerals are listed in order of decreasing modal abundance (Irvine, 1982). Phase contacts between macrolayers are commonly discordant ($<10^\circ$) with respect to contacts between the cyclic units (Fig. 2). Olivine-bearing macrolayers thin towards the distal part of the intrusion (SW), while Ca-poor pyroxene-bearing macrolayers thin towards the centre (NE). The complete macrolayer sequence within a cyclic unit is rarely developed in a single profile across the layering, but may be seen along strike in cyclic unit 6 (Fig. 1b). Most cyclic units (10 out of 12) show incomplete, or reduced sequences (at least one macrolayer is missing at the top and/or at the base), whereas two units (5 & 10) show an interrupted sequence (with one or more intermediate macrolayers missing). Ideal, incomplete and reduced cyclic units, have been interpreted as due to crystallization from large-scale double-diffusive magma layers along an inclined floor (Robins *et al.*, 1987; Fig. 2). Interrupted sequences are now ascribed to later intrusion of picritic sills (Tegner and Robins, this volume).

Cyclic unit 8

Cyclic unit 8 has been investigated in four traverses perpendicular to modal layering (Fig. 1b), as summarized in Fig. 3. Gabbronorite (pahC) is the dominant rock-type in profile 4 and forms a wedge-

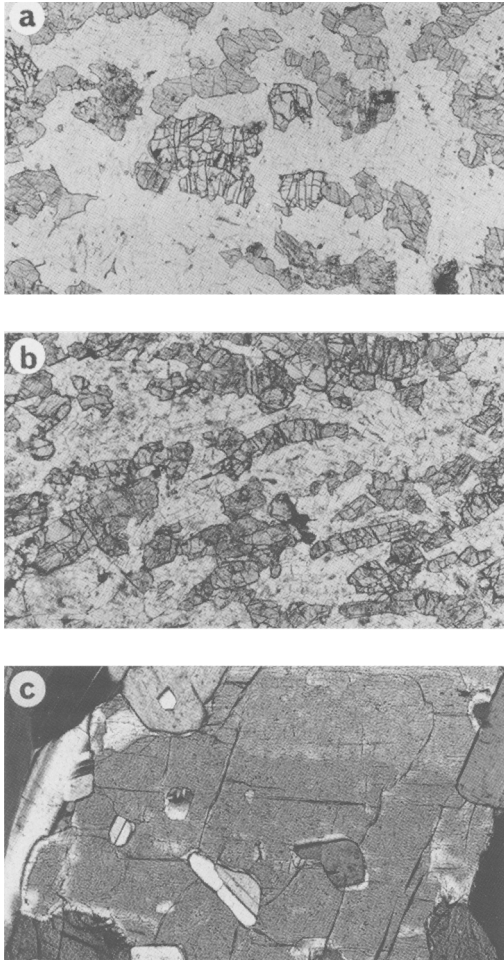


FIG. 4. Photomicrographs showing typical textures of (a) paoC and (b) pahC; width of photos is ~ 6 mm. (c). Resorbed plagioclase inclusions within Ca-rich pyroxene in paoC; width of photo is ~ 3 mm.

shaped macrolayer thinning towards the proximal parts of the intrusion, defining the top of cyclic unit 8. This is, however, not strictly correct in profile 2 where olivine-bearing gabbronorite (pahoC) occurs between ~ 65 – 95 m stratigraphic height; this level, nevertheless, is believed to correlate with the pahC in profiles 1, 3 and 4 as shown in Fig. 3. PahC is generally more fine grained and more leucocratic than the other rock-types (Fig. 4b), and consists of prismatic Ca-poor pyroxene (8–14%; < 4 mm long), plagioclase laths (60–67%; < 3 mm) and Ca-rich

pyroxene (22–27%) forming both subhedral, equant grains (< 2 mm) and more prismatic grains (< 3 mm long). Both Ca-rich and Ca-poor pyroxene include small, rounded and embayed plagioclase grains (Fig. 4c).

The gabbroic cumulates can be subdivided into two types: (1) ‘normal’ olivine gabbros (paoC) with approximately cotectic mineral proportions ($\sim p = 60$, $a = 30$ and $o = 10\%$); and (2) particularly olivine-rich melagabbros (oapC with $o = \sim 40$, $a = 30$ and $p = 30\%$). The non-cotectic modal composition in oapC is ascribed to crystal-melt reactions during later intrusion of picritic magma (Tegner and Robins, this volume). OapC occur in a thin wedge in the basal, proximal part of cyclic unit 8 (Fig. 3). In the following, it is assumed that the crystal-melt reaction took place on a volume-for-volume basis so that the space now occupied by oapC represents the original volume of paoC.

The wedge-shaped paoC macrolayer in cyclic unit 8 thins towards the distal part of the intrusion (Fig. 3). It has a typical mesocumulate texture with plagioclase laths (< 3 mm, 29–71%) forming a cumulus framework (Fig. 4a). Olivine (< 2 mm; 4–18%) forms subhedral grains while some of the Ca-rich pyroxene (22–46%) occurs as subhedral, prismatic grains (up to 4 mm long), the rest being anhedral, equant grains. Ca-poor pyroxene is typically intercumulus, occurring either as discrete interstitial grains or as oikocrysts. Ca-poor pyroxene locally rims olivine and Ca-rich pyroxene. Inclusions of small, rounded to euhedral plagioclase grains commonly occur within olivine and Ca-rich pyroxene (Fig. 4c).

Mineral chemistry

This study is based on ~ 1200 quantitative analyses of 49 samples from four traverses (Fig. 3). The analyses were performed at the Department of Earth Sciences, University of Aarhus, on a JEOL JXA-8600 microprobe equipped with four wavelength-dispersive spectrometers (WDS), using a focused electron beam of ~ 2 μm diameter, an accelerating voltage of 20 kV, and a beam current of 10 nA. The analyses of samples from profile 2 and 4 were run with two wavelength-dispersive spectrometers and the following elements were therefore measured by energy-dispersive methods (EDS): Si, Al and K in plagioclase; Si, Ca and Fe in pyroxene; Fe in olivine. At least two points in each of three grains were analysed within each sample using counting times of 40–60 s, or until the standard deviation (SD) on total counts was $< 1\%$ in the WDS case, whereas EDS analyses were collected for 120 s.

Representative mineral analyses are given in Table 1. Olivines are homogeneous ($2SD < 0.4\text{Fo}\%$) within

TABLE 1. Representative electron microprobe mineral analyses from cyclic unit 8

sample n°	H160	H83	H85	H200	H49	H202	H95	H200
rock-type	paoC	paoC	poaC	pahC	paoC	pahC	pahC	pahC
profile	1	3	3	4	2	4	3	4
mineral	olivine	olivine	plag	plag	cpx	cpx	opx	opx
SiO ₂ , wt. %	39.34	38.52	48.45	48.53	52.53	52.26	54.57	54.44
TiO ₂					0.50	0.78	0.23	0.27
Al ₂ O ₃			31.79	32.23	2.27	2.36	0.87	1.17
Cr ₂ O ₃					0.37	0.06	0.06	b.d.
FeO	15.93	21.76	0.24		5.08	5.89	13.39	14.49
MnO	0.22	0.27			0.14	0.17	0.23	0.31
NiO		0.17						
MgO	44.68	39.68			17.64	15.92	29.18	27.19
CaO			15.79	15.58	20.16	21.38	1.36	1.94
Na ₂ O			2.49	2.36	0.23	0.34	b.d.	b.d.
K ₂ O			0.10	0.29				
total	100.17	100.40	98.86	98.99	98.92	99.16	99.89	99.81
Mg#	83.3	76.7			86.1	82.8	79.5	77.2
An%			77.8	78.5				
formula based on:	4 oxygen atoms		8 oxygen atoms		6 oxygen atoms		6 oxygen atoms	
Si	0.991	0.996	2.244	2.242	1.937	1.936	1.955	1.965
Ti					0.014	0.022	0.006	0.007
Al			1.736	1.754	0.098	0.103	0.037	0.050
Cr					0.011	0.002	0.002	
Fe	0.336	0.470	0.009		0.157	0.182	0.401	0.431
Mn	0.005	0.006			0.004	0.005	0.007	0.009
Ni		0.003						
Mg	1.678	1.529			0.970	0.879	1.559	1.463
Ca			0.784	0.771	0.796	0.848	0.052	0.075
Na			0.224	0.211	0.016	0.024		
K			0.006	0.017				
total	3.010	3.004	5.003	4.995	4.003	4.001	4.019	4.000

b.d.=below detection limit (~ 0.05 wt.%); blank=not analysed; Mg#=100Mg/(Mg+Fe); An%=100Ca/(Ca+Na).

individual samples (Table 2). Both pyroxenes have larger 2SD (~ 2 Mg#) [Mg# = 100Mg/(Mg+Fe)] within individual samples, indicating that they are less re-equilibrated than the olivines. The focused beam provides sub-solidus compositions. The presence of exsolution lamellae in both pyroxenes (visible exsolution lamellae were avoided), however, may explain some of the variations in Mg#. The statistics imply that changes of >0.4 Fo% (olivine) and >2 Mg# (pyroxene) between individual samples are significant. Statistics are difficult to apply to plagioclase due to zoning and therefore we only report core compositions. The zoning is normal, i.e.

calcic cores (An₇₅₋₈₅) are surrounded by relatively sodic rims (down to \sim An₆₀). Differences in An% (100Ca/(Ca+Na)) between cores and rims increase considerably towards the distal part of the intrusion; weak zoning dominates in profiles 1 and 2, while strong optical zoning is observed in several samples from profiles 3 and 4.

Compositional variations

Cryptic variation in olivine (average Fo%) and Ca-poor pyroxene (average Mg#) across cyclic unit 8 within the four sample profiles are shown in Fig. 3.

TABLE 2. Variation of mineral compositions in representative samples as determined by electron microprobe

sample n° rock-type mineral	H49 paoC olivine		H52 paoC clinopyroxene		H200 pahC orthopyroxene	
	mean	2SD	mean	2SD	mean	2SD
Mg# in 15 grains in one sample	83.13	0.38	85.87	1.78	78.88	2.08
Mg# in 15 analyses in one grain	83.47	0.52	86.54	1.92	78.29	3.22

2SD=2 standard deviation, Mg#=100Mg/(Mg+Fe)

The conversion of paoC to oapC apparently does not change the composition of original cumulus minerals (Tegner and Robins, this volume). This is also suggested by the continuity between Fo% in paoC and oapC in profile 1 (Fig. 3). It is therefore assumed that mineral compositions in oapC represent that of the original paoC. The base of cyclic unit 8 is generally marked by minor regressions in olivine compositions in profile 1 (Fo_{84.3}–Fo_{84.7}) and 2 (Fo_{81.4}–Fo_{83.4}), and in Ca-poor pyroxene in profile 4 (Mg# = 78.4–82.4). In profile 3 an inflexion, shown by a thick sequence with constant Fo% in an overall decreasing trend, is taken to define the base of unit 8. The vertical cryptic variations through cyclic unit 8 indicate a weak, but distinct trend of decreasing Fo% and Mg# in Ca-poor pyroxene towards the top (Fig. 3). The Mg# numbers of Ca-rich pyroxene (not shown) generally mimic those of olivine, but the absolute changes are smaller.

In contrast to many other layered intrusions (e.g. Skaergaard and Bushveld), the most significant compositional variations are to be found along strike of the modal layering (Table 3). This is, for example, shown by olivines along the base of cyclic unit 8 (varying from Fo_{84.7} in profile 1 to Fo_{72.6} in profile 4; Fig. 3). A most striking example of the lateral variations can be seen along the phase contact between paoC and overlying pahC, where both olivine and Ca-poor pyroxene vary systematically towards more iron-rich compositions distally (Fig. 5). In other words, there is a discordant relation between phase layering and cryptic layering. This has, to the best of our knowledge, never been described in a layered intrusion.

Plagioclase compositions (cores) vary between An₇₅ and An₈₅ in both paoC and pahC of the four profiles, and there is no obvious correlation with Fo% (Fig. 6). Systematic lateral variations in plagioclase compositions do not exist (Table 3) and cryptic variations (based on average core compositions) related to macrolayers and cyclic units are non-existent or weak.

Discussion

The data presented here allow a qualitative analysis of some of the physical processes that took place during crystallization of a replenished magma chamber with an inclined floor. The main question to be addressed is whether the magma was significantly stratified due to double-diffusive convection, or whether the magma column was effectively continuously zoned.

Comparison with earlier work

Despite the recognition of later intrusive picritic sills in cyclic units 7–10 (Tegner and Robins, this volume), the data presented here confirm that the first-stage cumulates crystallized in a replenished magma chamber as originally proposed by Robins *et al.* (1987). The geometry of the paoC/pahC phase contacts with respect to boundaries between cyclic units 7, 8 and 9 are identical to those described by Robins *et al.* (1987). Cryptic variations showing a regression at the base of cyclic unit 8 and a normal fractionation trend towards the top of the unit is in accordance with magma replenishment. The wedge-shaped macrolayers and the lateral cryptic variation strongly suggest crystallisation along an inclined floor (Fig. 2).

Double-diffusive convection; theory, examples and problems

Research on fluid dynamics in aqueous solutions has given compelling evidence for persistent double-diffusive convection (Turner and Campbell, 1986 and references therein). Double-diffusive interfaces develop as a consequence of differences in the rates of diffusion of two components with opposing effect on the density of the solution (e.g. heat and composition). Liquids between double-diffusive interfaces (i.e. double-diffusive layers) are well

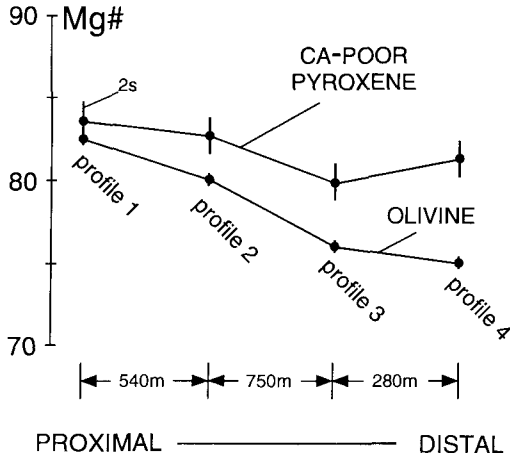


FIG. 5. Lateral variations in Mg# along the paoC/pahC phase contact of cyclic unit 8. Olivine compositions are from the top of the paoC and Ca-poor pyroxene from the base of the pahC macrolayer.

mixed and the densities, temperatures and compositions of individual layers are uniform. It is often suggested, both by fluid dynamicists and igneous petrologists, that comparable physical processes may apply to magma chambers (e.g. Turner and Campbell, 1986; Sparks and Huppert, 1987). This has revolutionized interpretations of many layered intrusions in terms of crystallization from compositionally-stratified magmas (Irvine *et al.*, 1983; Wilson and Larsen, 1985; Robins *et al.*, 1987; Nielsen and Wilson, 1991; Prendergast, 1991; Robins *et al.*, 1991; Wilson, 1992; Sørensen and Wilson, 1995). The common axiom is that emplacement of dense magma in the form of a turbulent fountain (Campbell and Turner, 1986) leads to the development of a zoned hybrid near the base of the magma chamber. This can break up into a number of convecting layers which would persist even if each of the layers was crystallizing simultaneously.

In several cases, however, the reality of double-diffusive convection in basic and ultrabasic magma chambers may be questioned. Three particular problems may be illustrated in the 'down-dip accretion' model (Fig. 7a) developed by Irvine and co-workers (Irvine, 1981; Irvine *et al.*, 1983). Firstly, fractional crystallization within double-diffusive magma layers must result in progressively decreasing Mg# within individual layers, i.e. the Mg# of cumulates along phase contacts should decrease towards the proximal parts of the intrusion (Fig. 7b). This is opposite to observations in Honningsvåg. Secondly, a consequence of the crystallization model in Fig. 7a and b is that the

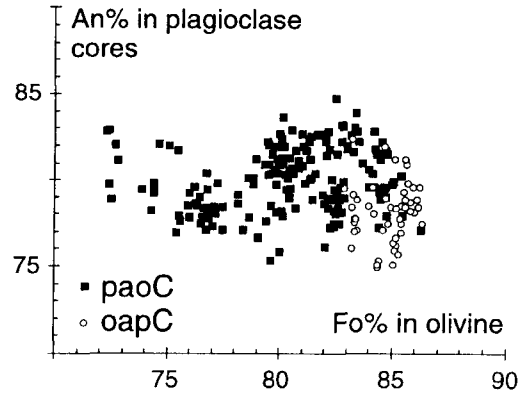


FIG. 6. An% in plagioclase vs. Fo% in olivine in paoC (samples from all four profiles) and oapC in profile 1.

intersection between one magma layer and the crystallization front, in theory, should result in step-like variations in Mg# along the modal layering (assumed to be parallel to the crystallization front). This has yet to be demonstrated in layered intrusions. Thirdly, discordant relations between phase- and modal layering in the distal part of two layered complexes, the Fongen-Hyllingen Complex (Wilson and Larsen, 1985) and the Great Dyke (Prendergast, 1991) have been interpreted in terms of discordant isotherms and isopleths (e.g. apatite-in) with respect to double-diffusive magma layers. This demands a delicate interplay between temperature and composition in order to maintain the constant density of individual double-diffusive layers, and seems to be in conflict with the basic concepts of double-diffusive convection.

Was the Honningsvåg magma effectively continuously-zoned?

The systematic lateral variations of the Honningsvåg cumulates demand a reappraisal of the compositional zonation in the magma chamber. Initially, however, it is necessary to justify several basic assumptions. Contacts between cyclic units, which are parallel to modal layering, are assumed to be synchronous surfaces reflecting the crystallization front, whereas phase contacts are diachronous (Robins *et al.*, 1987). Large-scale, penetrative convection is precluded by the systematic lateral cryptic variations along synchronous surfaces (e.g. along the base of cyclic unit 8) because a well-stirred magma would precipitate minerals of the same composition along any crystallization front (Wilson and Larsen, 1985). It is also assumed that magmas evolved towards lower densities during fractional crystallization

TABLE 3. Average mineral compositions at the base of cyclic unit 8

profile	1	2	3	4
lateral distance (m)	0	540	1290	1570
olivine (Fo%)	84.7	83.4	76.9	72.6
Ca-rich pyroxene (Mg#)	88.0	86.5	84.3	84.1
Ca-rich pyroxene (wt.% Cr ₂ O ₃)	0.59	0.43	0.32	0.24
Ca-rich pyroxene (wt.% TiO ₂)	0.61	0.46	0.51	0.51
Ca-poor pyroxene (Mg#)*	83.6	82.7	79.8	81.3
plagioclase (An%)	79.0	83.1	77.8	80.9

* at the base of the pahC macro layer of unit 8

(Robins *et al.*, 1987). This assumption is, admittedly, debatable because the fractionation densities of paoC and pahC are lower than the densities of dry, tholeiitic magmas (Sparks and Huppert, 1984). However, as discussed by Robins *et al.* (1987), even small amounts of components with large molar volumes (e.g. water) may lower magma densities significantly (Campbell *et al.*, 1978). Most importantly, the validity of the basic assumptions noted above can be assessed by the success or failure of the crystallization models in explaining the observed cryptic variations.

The lateral compositional variations described here suggest that crystallization from large-scale, double-diffusive magma layers cannot have produced the cumulates of Intrusion II in Honningsvåg. Alternatively, it can be imagined that the magma is continuously-zoned. A fountaining replenishment event, in which the hybrid displays an upwardly decreasing ratio of new to residual magma (Campbell and Turner, 1989), is likely to result in a continuously-zoned magma column. A stable density gradient is plausible because the new magma is likely to be denser (more primitive) than the residual magma. Fractional crystallization, however, inevitably leads to compositional convection. When penetrative, whole-chamber convection is excluded, as is the case here, the formation of double-diffusive magma layers is the only plausible way to accommodate compositional convection. The intriguing question is: how thick was each double-diffusive layer? In Honningsvåg, the maximum thickness can be estimated because the cumulates show a fairly continuous decrease in Fo% in 9 samples covering ~2200 m along the base of cyclic unit 8 (Robins *et al.*, 1987). If the floor dipped at 5 degrees, the 9 samples correspond to one sample each ~21 m of a horizontally-stratified magma column, i.e. double-diffusive layers must have been thinner than ~21 m. It is therefore concluded that

double-diffusive layers, if they existed, were relatively thin compared to the actual thickness of macrolayers in Honningsvåg. This leads us to the conclusion that the Honningsvåg magma chamber was stratified but effectively continuously-zoned.

Crystallization during differential migration of isopleths

The lateral variations in mineral chemistry along the paoC/pahC phase contact necessitate a complex interplay of physical processes. This stratigraphic reflection of the Bowen-Anderson olivine–melt reaction is due to a_{SiO_2} increasing, during fractional crystallization, to some critical value. The main feature of the paoC/pahC contact is that the compositions of the last olivine below, and the first Ca-poor pyroxene above, have higher Mg# in the proximal parts of the intrusion (Fig. 5), implying increasing a_{SiO_2} along the paoC/pahC contact towards the central part of the intrusion. The a_{SiO_2} of a magma can increase not only as a result of fractional crystallization but also by contamination resulting from assimilation of silica-rich country rocks. Isotopic evidence for contamination is not yet available but, since xenoliths of hornfelsed graywacke are abundant within the cumulates, we assume that assimilation of the metasedimentary country rocks was as significant as in other mafic complexes emplaced into comparable country rocks (Tegner, 1994; Sørensen and Wilson, 1995).

In a zoned magma chamber, horizontal isopleths will migrate in response to both fractional crystallization and contamination. The Mg#, for example, will decrease upwards in an effectively continuously-zoned magma produced by magma mixing as described above. Isopleths of Mg# will subside as the result of fractional crystallization at the base of the chamber (in periods uninterrupted by magma recharge). Silica activity, on the other hand,

pyroxenes) but not plagioclase compositions; and (2) plagioclases and olivines crystallized from compositionally different magmas.

Re-equilibration of the Fe/Mg ratio in mafic minerals takes place more readily than Na/Ca re-equilibration in plagioclase (Morse, 1984). The restricted zoning of the mafic minerals (Table 2) suggests local homogenization, whereas significant compositional zoning suggests that homogenization was less complete in plagioclase. However, any model involving extensive postcumulus modification would not be able to account for the systematic lateral changes in olivine and pyroxene compositions.

The occurrence of anhedral plagioclase inclusions in cumulus olivine and pyroxene (Fig. 4c) is comparable to descriptions from the Bushveld (Eales *et al.*, 1991) and Kap Edvard Holm Complexes (Tegner and Wilson, 1995), where a decoupling of the compositions of plagioclase and mafic minerals exists at certain stratigraphic intervals. This decoupling has been ascribed to the incorporation of pre-existing, suspended plagioclases of uniform composition into either an advancing crystallization front (Kruger and Marsh, 1985) or into a hybrid magma produced during influx of new, more-primitive magma (Eales *et al.*, 1990; Eales *et al.*, 1991; Tegner and Wilson, 1995). It is possible that similar processes may have occurred in the Honningsvåg chamber. Cumulates formed in this way are hybrids and represent mixtures of crystals precipitated from compositionally different magmas.

Conclusions

New data from Intrusion II of the Honningsvåg Intrusive Suite suggest that large-scale stratification of mafic magma chambers by double-diffusive convection may be unlikely.

Replenishment apparently resulted in the formation of an effectively continuously-zoned, hybrid magma column.

Subsequent crystallization of the compositionally-zoned magma along an inclined chamber floor can satisfactorily explain both strong lateral compositional variations and the wedge-shaped geometry of macrolayers.

The Honningsvåg magma chamber was effectively continuously-zoned and double-diffusive layers must have had thicknesses considerably less than the cumulate macrolayers.

Differential migration of Mg# and a_{SiO_2} isopleths as a consequence of fractional crystallization accompanied by assimilation of country rocks, is inferred from the discordant relations between cryptic layering and the paoC/pahC phase contact.

Decoupling of plagioclase compositions from the coexisting mafic phases is probably the result of the

capture of pre-existing plagioclase crystals into the cumulates that formed from the zoned magma.

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