

FINE-SCALE GRADED LAYERS IN THE FONGEN-HYLLINGEN GABBROIC COMPLEX, NORWAY

PETER THY*, NIELS NYBO JAKOBSEN, J. RICHARD WILSON

Department of Geology, University of Aarhus, DK-8000 Aarhus C, Denmark

ABSTRACT

Fine-scale modal layering in the Fongen-Hyllingen gabbroic complex in the central Scandinavian Caledonides features rhythmic recurrence of mineral assemblages. Single layers, defined as starting by an increase in mafic minerals, generally range in thickness from a few millimeters to a few centimeters. In the olivine - clinopyroxene - orthopyroxene - plagioclase cumulus zone, modally graded layers begin with a concentration of clinopyroxene, succeeded by an increase in olivine, and terminated by an increase in plagioclase. Orthopyroxene appears locally between the clinopyroxene- and olivine-rich zones. In the more evolved Fe-Ti oxide - olivine - pyroxene - plagioclase cumulus zone, two types of modal grading can be distinguished. The dominant type features complementary variation between plagioclase and olivine; the less important type comprises layers which start with olivine, followed by increasing Fe-Ti oxides, and terminated by increasing plagioclase. In both cumulate zones, incomplete layers occur when any or several of the phases are absent or fail to increase. It is suggested that fine-scale microsegregation developed the graded layers in an advancing stagnant boundary-layer due to diffusion and temperature-controlled oscillations on the magma-chamber floor.

Keywords: rhythmic layering, modal variation, microsegregation, gabbroic intrusion, Fongen-Hyllingen complex, Norway.

SOMMAIRE

La stratification définie par des variations modales à petite échelle dans le complexe gabbroïque de Fongen-Hyllingen, dans les Calédonides scandinaves centrales, en Norvège, dépend de la répétition rythmique des assemblages de minéraux. Une strate individuelle, qui commence, par définition, par une augmentation dans la proportion des minéraux mafiques, varie de quelques millimètres à quelques centimètres en épaisseur. Dans la zone de cumulats à olivine - clinopyroxène - orthopyroxène - plagioclase, des strates montrant une gradation modale commencent par une concentration en clinopyroxène, suivie d'une augmentation en olivine, et finalement par une augmentation en plagioclase. L'orthopyroxène fait son apparition localement, entre les zones à clinopyroxène et à olivine. Dans la zone de cumulats plus évolués à oxydes Fe-Ti - olivine - pyroxène - plagioclase, on distingue deux types de clas-

sement modal. Le type dominant montre une variation complémentaire dans les proportions de plagioclase et d'olivine; l'autre type, moins répandu, contient des strates qui commencent par l'olivine, suivi d'une augmentation des oxydes Fe-Ti, et qui finissent par le plagioclase. Dans les deux zones de cumulats, on peut trouver des strates incomplètes, dans lesquelles une ou plusieurs des minéraux sont absents or n'augmentent pas. Une microségrégation à petite échelle serait responsable des strates classées dans une zone stagnante devant le front de croissance qui reflète la diffusion et les oscillations thermiques sur le plancher de la chambre magmatique.

(Traduit par la Rédaction)

Mots-clés: stratification rythmique, variations modales, microségrégation, complexe intrusif gabbroïque, Fongen-Hyllingen, Norvège.

INTRODUCTION

A long-standing consensus in igneous petrology has been that the action of currents and gravity sorting of primocrysts in magma chambers are required to produce modally layered structures (Wager & Brown 1968). A variety of evidence, however, has indicated that layered structures more likely formed as a result of heterogeneous nucleation on the walls, roofs, and particularly the floors of magma chambers (*e.g.*, Campbell 1978, 1987, McBirney & Noyes 1979). Critical evidence in favor of gravitative settling or deposition (or both) from magmatic currents has been narrowed to features such as fragmental layers and size-graded layers (Irvine 1987). Only sparse textural and structural studies of fine-scale layering exist in the literature. This paper concerns two examples from the Fongen-Hyllingen complex. The results imply that the layers formed by oscillating chemical processes along an advancing front of solidification on the floor of the magma chamber.

LAYERING IN THE FONGEN-HYLLINGEN COMPLEX

The Fongen-Hyllingen intrusion is a layered, differentiated, gabbroic body situated in the central Scandinavian Caledonides (Wilson *et al.* 1981). Nearly 10,000 meters of modally layered cumulates occur, showing extreme cryptic variation. At least seven major reversals with stratigraphic height have been identified, reflecting periodic intrusion of magma.

*Present address: NASA, Johnson Space Center, SN4, Houston, Texas 77058, U.S.A.

In a detailed study of the vertical and lateral compositional variations in the southern part of the complex (the Hyllingen Series), Wilson & Larsen (1985) showed that cryptic and phase layering became increasingly discordant to modal layering as one approaches the southern margin. For example, at one stratigraphic level in the Hyllingen area, olivine and plagioclase vary systematically over 7 km from Fo₇₅ to Fo₁₃ and An₆₃ to An₄₂, respectively, along the strike of modal layering approaching the margin. Consequently, the modal layering does not represent an isothermal surface. This evidence conflicts with traditional crystallization models involving large-scale convection and crystal settling. It is also difficult to envisage the formation of graded layers from density currents descending from the flanks of the magma reservoir for two main reasons. Firstly, the modal layering strikes directly into the margin of the magma chamber where layered rocks inter-finger with the country-rock envelope and show no indication of crystallization inward from the wall. Secondly, the variation in mineral compositions along the strike of modal layering is incompatible with the relatively rapid deposition of crystals over a large surface from a dense current. Wilson & Larsen (1985) suggested that *in situ* crystallization from stratified magma occurred along an inclined floor. Modal layering developed concordantly with the crystallization front, whereas cryptic and phase layering developed almost parallel to the liquid stratification.

Modal layering throughout the Fongen-Hyllingen complex displays a variety of erosional and deformational structures, some of which point to the action of currents (Thy & Wilson 1980, Wilson *et al.* 1981, Thy 1983). Layer thicknesses range from dominantly thin (m-dm) to fine (cm-dm), and the layers are either uniform or modally graded. Some layers show a marked variation in grain size (Thy & Esbensen 1982), and both normal and reverse density-grading can be observed, although the first is by far the more common. Contacts between layers may be sharp or gradational, and although planar lamination is common, mineral lineations and grain-size grading are rare. The layered rocks are dominantly medium-grained granular adcumulates, with poikilitic varieties developed locally (Wager *et al.* 1960, Irvine 1982).

Material eroded by current action from crystallizing layered intrusions must have been transported down-current and, presumably, have been redeposited. This explains fragmental layers and possibly their matrix, but some or most of the material eroded from only partly consolidated cumulates may have been as discrete (or composite) grains. There is clear evidence in the Fongen-Hyllingen intrusion for local erosion by currents, and fragmental layers also occur sporadically. The question arises as to

whether layered rocks formed by the redeposition of discrete grains can be distinguished from those formed by *in situ* crystallization, and whether modal variations of fine-scale layers bear evidence of their origin.

FINE-SCALE GRADED LAYERS

In order to include contrasting cumulus assemblages, samples from two occurrences representative of the fine-scale layering were selected. Sample A was collected from the olivine - clinopyroxene - orthopyroxene - plagioclase cumulus zone (Thy 1983), and sample B from the olivine - clinopyroxene - orthopyroxene - plagioclase - Fe-Ti oxides cumulus zone (Wilson & Larsen 1985). Sample A (Fig. 1A) features fine-scale layering, with individual laminae typically a few mm to 1 cm thick [see also Thy (1983, Fig. 4)]. Olivine and plagioclase compositions are Fo₆₇ and An₅₅, respectively. Sample B (Fig. 1B) comes from near the center of a major gradual compositional regression over 400 m (Wilson & Larsen 1985); olivine and plagioclase compositions are Fo₄₆ and An₄₈, respectively.

Thin sections were prepared spanning the entire samples, perpendicular to the layering, and modal variations were determined by point-counting techniques. About 100 determinations, each of 600-800 counts, were made for sample A, and 86 determinations of 300-500 counts were made for sample B.

Mineral zoning and unequivocal mineralogical evidence for a trapped interstitial liquid (intercumulus) is rarely observed in the samples. It is significant that interstitial and equigranular (cumulus) textured phases, in general, cannot be discriminated by mineral chemistry and that marginal zoning in plagioclase can be identified only rarely. This suggests that an interstitial or poikilitic texture cannot be equated *a priori* with an intercumulus origin (*e.g.*, crystallized from trapped liquid). The Fongen-Hyllingen samples are adcumulates with between 2 and 10% poikilitic phases in sample A, and from 8 to 20% in sample B. The samples may classify as heteradcumulates (Wager *et al.* 1960) or simply as poikilitic adcumulates (Irvine 1982). The actual amount of intercumulus material (or the residual porosity), nevertheless, is difficult to estimate because there are usually at least four cumulus phases present and the amount of postcumulus overgrowth is unknown. Postcumulus overgrowth on olivine and pyroxene cannot readily be identified because of homogenization during cooling. Furthermore, distinction between intercumulus and cumulus phases is rather subjective, especially for opaque minerals. On this basis, the amount of intercumulus material in sample A is estimated to be <2% and for sample B somewhat higher (<5%). The majority of this interstitial material is Fe-Ti oxides, rarely showing

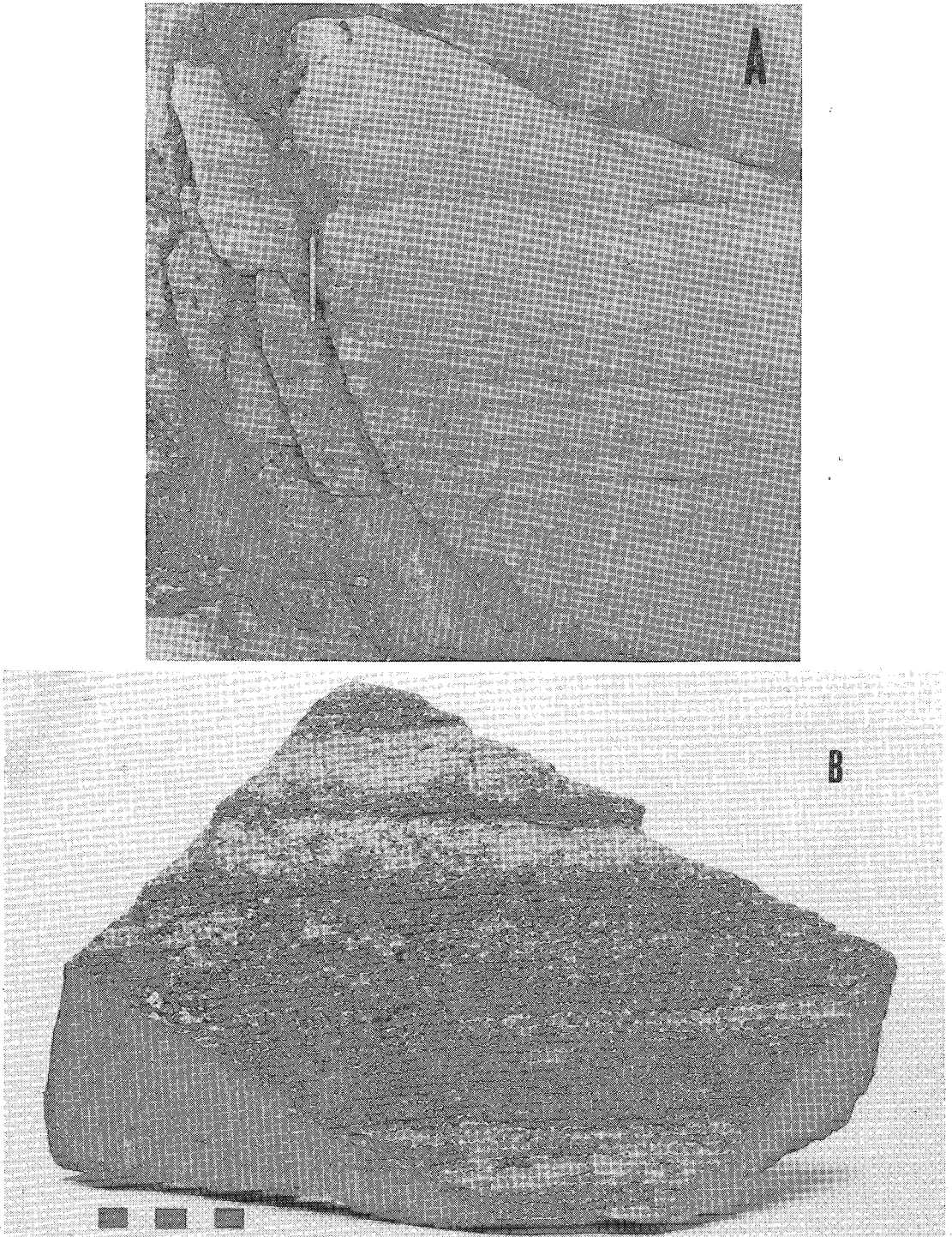


FIG. 1. A. Fine-scale layering in two-pyroxene gabbro from the central part of the Fongen-Hyllingen complex. Pencil for scale is 15 cm long and rests on the sample A used in this study. B. Fine-scale layered, Fe-Ti oxide-bearing gabbro sample from the southern part of the Fongen-Hyllingen complex (Hyllingen Series) used in this study as sample B. Scale is 5 cm.

detectable zoning (Thy 1982), and calcic amphiboles typically occurring in coronas on the Fe-Ti oxides (Thy 1982).

Sample A

Macroscopically (Figs. 1A, 2A), sample A has 9 mesocratic laminae alternating with leucocratic laminae. The sample block is 20 cm thick; individual macroscopic laminae range from about 3 to 0.5 cm. Mineralogically, the sample consists of plagioclase, olivine, clinopyroxene, and orthopyroxene, with minor Fe-Ti oxides and brown calcic amphibole. The textures are dominated by a subhedral equigranular (or adcumulate) fabric, but poikilitic phases occur throughout the sequence. Olivine and plagioclase mostly display an equigranular texture, whereas clinopyroxene and orthopyroxene can be either equigranular or interstitial. High concentrations of a pyroxene phase can be correlated with an equigranular fabric. This relationship is particularly shown by orthopyroxene, which in a few pyroxene-rich laminae has a slightly elongated granular form, but occurs throughout the sequence as an interstitial or poikilitic phase. Fe-Ti oxides and calcic amphibole occur only interstitially, the latter often as rims on the former.

The main modal variations (in volume %; Fig. 2A) are in plagioclase (average 50%, range 25–70%), olivine (31%, 10–65%), and clinopyroxene (14%, 0–45%). Orthopyroxene reaches 18% in some horizons, but averages only 3%. Fe-Ti oxides and brown hornblende both average about 1%, but show local concentrations up to about 5%. The bases of the micro-units in Figure 2A are defined by plagioclase falling below 50%, associated with a complementary increase in mafic minerals. The nine distinct micro-units defined in this way generally reveal a regular sequence in the modal variations. The definition of the base and top of the micro-units coincides with the visible macroscopic layering.

Six micro-units (A2, A3, A5, A6, A7, and A9) feature, from base to top, successive peaks of clinopyroxene, olivine, and plagioclase. Micro-unit A4 shows normal density-grading between plagioclase and olivine, with a clinopyroxene peak near the base. Cumulus orthopyroxene is present only in units

A1, A2, and A9, where it either coincides with or peaks after clinopyroxene. The orthopyroxene peak in A7 is due to a single, large poikilitic grain occurring just above the clinopyroxene peak at the base of the unit. The Fe-Ti oxides (and amphiboles) are interstitial, and where they occur in significant amounts they appear to be concentrated at the same stratigraphic intervals as the mafic minerals. These relations suggest that the mineral sequences may not be related to the cumulus or interstitial textural status of the crystallizing phases.

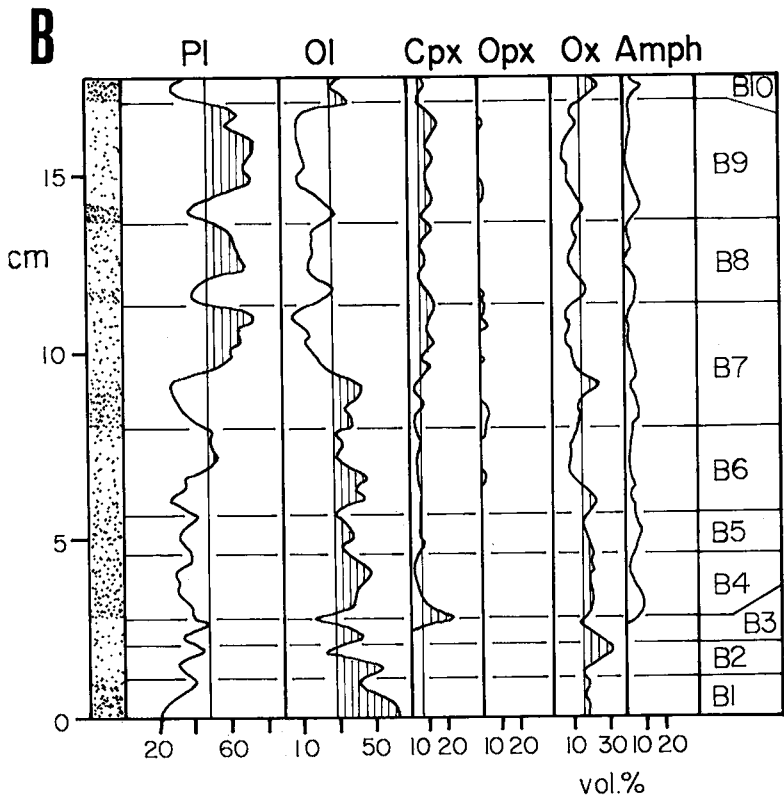
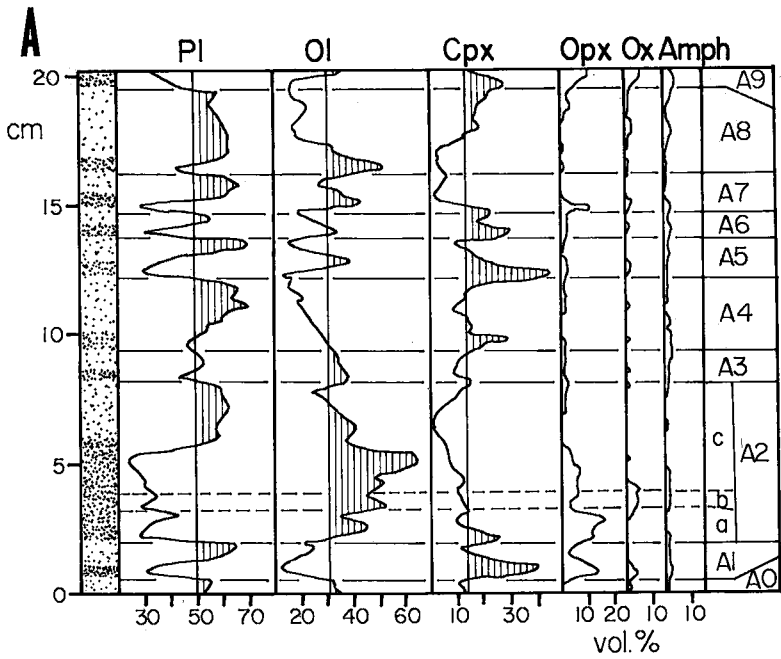
There is a regular sequence in the modal abundances of the major minerals in the micro-units (Figs. 2A, 3A), most of them starting with increasing clinopyroxene followed, in many cases suddenly, by increasing olivine (and orthopyroxene), and terminated by increasing plagioclase. Two micro-units depart from this sequence in that olivine fails to show any significant increase (A1 and A4), and in A8 olivine precedes clinopyroxene. Apparently incomplete micro-units also occur where clinopyroxene is missing (A3) or is only present in minor amounts. Unit A2 may be further divided into at least three subordinate units (A2a-c). Consequently, although the usual sequence seems to be plagioclase - clinopyroxene - (orthopyroxene) - olivine - plagioclase, and so on, one or more of these phases may be missing or fail to show an increase in modal proportions.

Sample B

The lowest 7 cm of sample B (Figs. 1B, 2B) are macroscopically homogeneous, followed by 4 distinct plagioclase-rich laminae in the upper 11 cm. The bulk composition of the sample is dominated by plagioclase (average 47%, range 22–77%), olivine (28%, 5–60%), and Fe-Ti oxides (15%, 4–31%), whereas clinopyroxene (7%, 0–24%) and brown calcic amphibole (3%, 0–13%) are subordinate. Orthopyroxene is locally present in minor amounts (0.4%). Olivine and plagioclase are generally equigranular, whereas clinopyroxene and Fe-Ti oxides may be either granular or interstitial. Brown hornblende occurs exclusively as a rim on the Fe-Ti oxides, whereas orthopyroxene forms rare, isolated poikilitic grains.

The criterion used to define micro-units in the

FIG. 2. Modal variation (vol.%) in samples A and B. The values plotted are the means of two adjacent determinations. The distance between counts was $\frac{1}{2}$ mm in both *x* and *y* directions. The left-hand column indicates the macroscopic appearance of the samples. Average values for the main minerals are shown by the vertical lines and shading shows the concentrations above average values. The samples are divided into micro-units based on decreasing plagioclase and increasing mafic minerals. Pl plagioclase, Ol olivine, Cpx clinopyroxene, Opx orthopyroxene, Ox Fe-Ti oxides, Amph calcic amphibole. A. Sample A. The micro-unit boundaries are based on <50% plagioclase, except that sub-units of A2 are based on <34%



plagioclase. Only the top and base, respectively, of units A0 and A9 are shown.
 B. Sample B. Base of unit boundaries defined either by plagioclase falling below 50% (B7-B10) or below 40% (B1-B6).

upper part of the sample (B7-B10) is <50% plagioclase, as used for sample A and corresponding to the macroscopic layering. In the lower part a value of plagioclase <40% has been used (B1-B6). This allows the definition of a total of 10 micro-units (Fig. 2B). Changing these values within reasonable limits does not significantly affect the conclusions drawn on the sequence of mineral abundances.

Most of the micro-units have olivine concentrations at the base (Figs. 2B and 3B). There are significant positive correlations in the abundance of olivine both with Fe-Ti oxides and brown hornblende. Micro-unit B4 shows a sharp peak of clinopyroxene at the base (absent in B1-B3), accompanied by slightly increasing hornblende and followed by increasing olivine. The main modal variation in sample B is an inverse relationship between olivine and plagioclase, but four units (B6, B8-B10) show successive peaks in olivine, Fe-Ti oxides, and plagioclase.

DISCUSSION

Gravitational and current sorting

According to the terminology of Irvine (1982), the

micro-units should be described by their internal features as modally graded. In sample A, the degree of enrichment in any one of the main cumulus phases may differ considerably from unit to unit, but eight of the nine units show the same style of variation (Fig. 3A). In sample B most of the variation (Fig. 3B) is between plagioclase and olivine, but Fe-Ti oxides also frequently show a regular pattern. It would be difficult to argue in favor of a gravitational-settling or current-sorting model for the following reasons.

Firstly, in terms of mineral density-grading the observed primocryst sequence should be Fe-Ti oxides, olivine, clinopyroxene, and plagioclase, a sequence that cannot be convincingly demonstrated in either of the samples. In particular, the concentration of clinopyroxene at the bases of the micro-units in sample A does not support a gravity-controlled process. Although relative density is important for crystal settling, grain size is vital for the settling rate because the radius of spheres is squared in Stokes Law. However, grain diameters measured at selected levels in the two samples do not reveal any variation likely to be hydrodynamically significant (plagioclase average diameter 0.6 ± 0.3 mm; clinopyroxene 0.6 ± 0.4 mm; olivine 0.5 ± 0.2

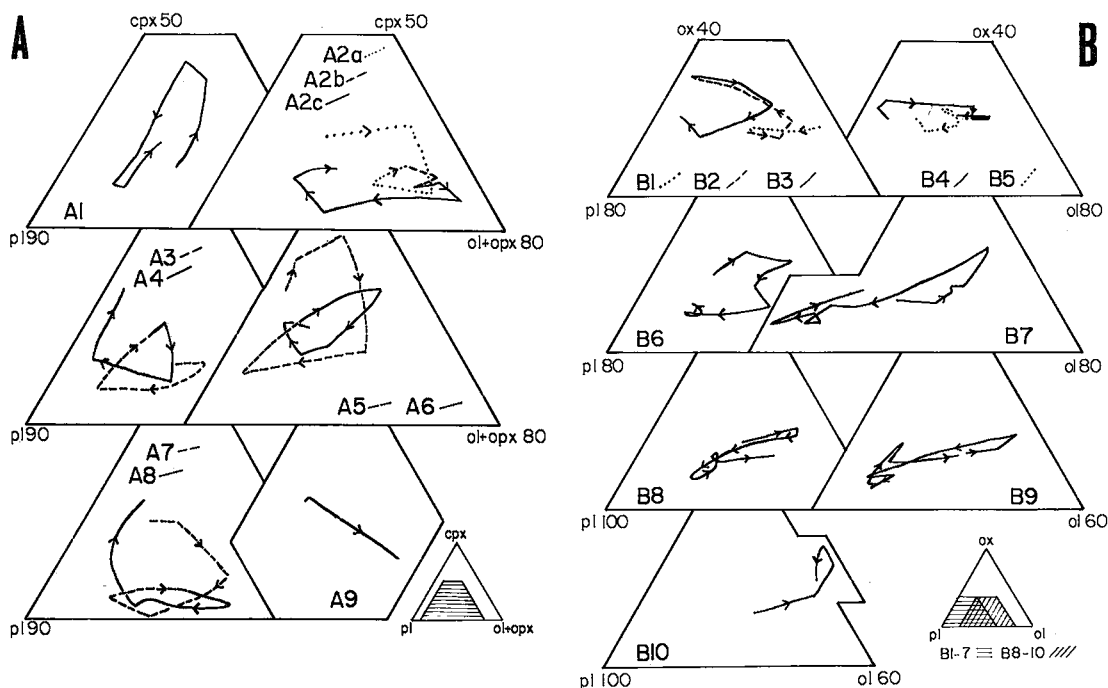


Fig. 3. Modal variation of the major cumulus phases in the individual rhythmic units. A. Variation between plagioclase (pl), clinopyroxene (cpx), and olivine plus orthopyroxene (ol+opx) in sample A. Fe-Ti oxides and calcic amphiboles in general occur in minor amounts and are omitted from the projection. B. Variation between plagioclase (pl), olivine (ol) and Fe-Ti oxides (ox) for sample B. With a few minor exceptions, clinopyroxene does not vary significantly with stratigraphic height (Fig. 2B) and is omitted from this Figure.

mm). Although the sizes of the original grains in the laminae are unknown, the amount of postcumulus modification could not have obliterated any hydrodynamically significant size-grading (*cf.* Jackson 1961, pp. 30-37, Irvine 1980a).

Secondly, plagioclase could be expected to have been buoyant (*cf.* Campbell *et al.* 1978) in the relatively iron-rich parental magmas considered here (Wilson *et al.* 1981). Irvine (1980a) proposed that plagioclase could be transported to and deposited on the bottom of magma chambers by surge-type density currents in which plagioclase was kept in suspension with mafic minerals. A current-deposition model is, nevertheless, not considered likely because of the relatively scarce occurrence of associated erosional features, slump structures, fragmental layers, and, in particular, grain-size graded layers.

Thirdly, rhythmic variation is often shown by the interstitial as well as by the cumulus phases. Furthermore, a mineral present as a cumulus phase frequently also occurs interstitially, either in the same layer or in adjacent layers. Interstitial phases commonly appear to have crystallized from the liquid with which the adcumulus phases equilibrated. For example, olivine cumulates with up to 30% interstitial Fe-Ti oxides only occur within the Fe-Ti oxide cumulus zone (Thy 1983). Except for a very small amount of true intercumulus material, most interstitial phases appear to have nucleated and grown in an open system which was compositionally controlled by the overlying magma. This points to a slow crystallization rate.

These factors, combined with the critically important evidence for systematic lateral compositional variation along the strike of modal layering (Wilson & Larsen 1985), are not in favor of the fine-scale graded layers having been formed by gravitative settling and current deposition.

Formation of the adcumulus textures

Adcumulus textures were believed by Wager *et al.* (1960) and Wager (1963) to reflect low accumulation rates and isothermal diffusion-controlled consolidation under slightly supercooled conditions (*i.e.*, secondary adcumulates). However, Hess (1972) pointed out that diffusion likely would be too slow to explain the development of adcumulates, and he suggested that compositional convection of the pore fluid played a role. This suggestion has been further elaborated by Tait *et al.* (1984) and Morse (1986). Irvine (1980b) suggested that infiltration metasomatism and re-equilibration with an upward-moving intercumulus liquid, which was expelled as a result of compaction of the cumulus pile, could produce adcumulates (*cf.* Campbell (1987) for a discussion). There is no convincing evidence for infiltration metasomatism in at least the Hyllingen Series

(Wilson & Larsen 1985). In addition, subsolidus annealing processes in the cumulus pile, driven by the minimization of surface energy, have been widely suggested (*e.g.*, Cawthorn *et al.* 1983). All these models assume relatively high initial porosity, but only annealing is independent of gravity and can explain monomineralic plagioclase adcumulates in which the residual liquid will be relatively dense (Campbell 1987). Nevertheless, recent experimental work by Walker *et al.* (1985) suggests that sintering in the presence of a liquid can produce adcumulate textures with a very low initial porosity (*i.e.*, primary adcumulates).

The interpretation of adcumulate textures has generally not considered that the rocks are usually in local textural equilibrium so that the present geometry of the cumulus grains certainly does not represent the geometry when cumulus grains came into contact in the presence of a melt (Hunter 1987). Although the adcumulates of the Fongen-Hyllingen complex presumably reflect low accumulation rates, our present understanding of solidification processes in magma chambers and the role of textural equilibration evidently does not allow unequivocal evaluation of the adcumulate textures. It seems that the consolidation front followed relatively closely behind the cumulate-magma interface to account for the general lack of intercumulus crystallization. The occurrence of poikilitic adcumulate phases, showing limited chemical variation, points to nucleation and growth-rate-controlled processes (Wager *et al.* 1960). These requirements are best achieved by *in situ* or bottom crystallization.

Bottom crystallization

Several workers have explained fine-scale layered structures in mafic and ultramafic rocks as a result of *in situ* processes. Among these, Kanaris-Sotiriou (1974) proposed a model involving concentration of the expelled solute from a solidifying cumulus pile to explain mafic layers. Dunham (1965) suggested that "matrix layering" in the Rhum Complex is the result of rhythmic variation in phases crystallizing from the interstitial liquid in a cumulate mush. There is a long tradition of interpreting diversity in cumulates as a result of oscillatory homogeneous nucleation in supercooled magmas (*e.g.*, Wager 1959, Hawkes 1967, Goode 1976, Maaløe 1978). The indications from the layering observed in this study are that crystal growth occurred on, or close to, the solidification front, as suggested by Campbell (1978) and McBirney & Noyes (1979). Nucleation probably occurred dominantly either on pre-existing grains of the same type (self-nucleation) or heterogeneously on grains of a different type (heterogeneous nucleation) (Campbell 1987). McBirney & Noyes (1979) suggested that oscillatory nucleation could result

from competition between time-dependent thermal and chemical diffusion in a thin boundary-layer at the crystallizing front. Nucleation of a phase would deplete the liquid in a zone initially moving faster than the zone of cooling. With time, growth rate would be expected to slow and the thermal conductivity would overtake and initiate a repeated burst of nucleation.

Harker (1909), and later Maaløe (1978), attempted to extend understanding of oscillatory processes to binary systems, and Petersen (1985) suggested the use of pseudo-binary diagrams, reducing the problem of multicomponent systems to complementary compositions and phases. The model used by Maaløe (1978) for the development of rhythmic layering is based on systematic variations in the nucleation of cumulus minerals. This requires that the magma in contact with the crystallization front be supersaturated; crystallization of one phase changes the composition of the magma so as to influence the nucleation rates of the other cumulus phases. Multicomponent liquids are likely to develop overlapping and telescoping concentration gradients, bringing subsequent phases to nucleate. Competition between nucleation, growth, and cooling rates would probably control the actual sequence of phase appearance, texture, and composition, reflected in an oscillating liquid composition which approaches equilibrium relations. The textural range from equigranular textures (adcumulates) to interstitial and poikilitic varieties may reflect local changes in growth rate due to either variation in degrees of supercooling or composition. In the cases discussed in this paper the liquids were multisaturated with either olivine, clinopyroxene, orthopyroxene, and plagioclase (sample A), or Fe-Ti oxides, olivine, clinopyroxene, and plagioclase (sample B). Systematic oscillations about equilibrium relations probably resulted in the observed sequence in the fine-scale layers. Failed nucleation of one or more phases can be achieved by a temporary rise in interface temperature due to the ineffective removal of latent heat of nucleation and growth.

The average modal composition of sample A (51% pl, 17% px, 32% ol) is more mafic than cotectic proportions in basalts (e.g., 82% pl, 8% px, 11% ol; Bryan 1983). Although not suggested by the phase assemblage, this may be an effect of non-basaltic parental liquids. Alternative possibilities are: 1) all the cumulates are mafic cumulates, 2) non-equilibrium crystallization, or 3) relatively high-pressure (approximately 5 kbar) crystallization shifting the cotectics toward a higher proportion of olivine, as suggested by Thy (1983).

The observed sequence of nucleation is not identical to the sequence of cumulus-phase appearance observed in the complex (Wilson *et al.* 1981). However, by redefining the bases of individual

graded laminae (micro-units) for sample A to start with a peak in olivine, the general modal sequence could be defined as olivine, plagioclase, clinopyroxene, (orthopyroxene), returning to olivine *etc.*, so that the pyroxene laminae form the tops of distinct units. This conflicts with the traditional definition of graded layers, where the base is usually defined by an increase in mafic minerals, but this sequence would be consistent with the observed sequence of appearance of cumulus minerals in the Fongen-Hyllingen complex. An interesting consequence, which deserves future supporting work, is that a single graded layer, perhaps only a few mm thick, may mimic the same crystallization sequence as featured by a stratigraphic cumulate sequence several km thick.

CONCLUSIONS

The fine-scale rhythmic variation of mineral phases in two samples from the Fongen-Hyllingen complex points to oscillatory chemical and thermal processes occurring at the solid-liquid interface. It is suggested that nucleation- and growth-rate-controlled processes oscillating about equilibrium, coupled with multisaturated relations, produced the observed mineral sequences.

ACKNOWLEDGEMENTS

Comments from R.F. Emslie, T.N. Irvine, D.A. Morrison, S.A. Morse, and J.S. Petersen greatly improved the manuscript. Work on the Fongen-Hyllingen complex has been supported by the Danish Natural Science Research Council and the Carlsberg Foundation.

REFERENCES

- BRYAN, W.B. (1983): Systematics of modal phenocryst assemblages in submarine basalts: petrologic implications. *Contr. Mineral. Petrology* **83**, 62-74.
- CAMPBELL, I.H. (1978): Some problems with the cumulus theory. *Lithos* **11**, 311-323.
- _____ (1987): Distribution of orthocumulate textures in the Jimberlana intrusion. *J. Geol.* **95**, 35-54.
- _____, ROEDER, P.L. & DIXON, J.M. (1978): Crystal buoyancy in basaltic liquids and other experiments with a centrifuge furnace. *Contr. Mineral. Petrology* **67**, 269-377.
- CAWTHORN, R.G., MCCARTHY, T.S. & DAVIES, G. (1983): Vertical chemical gradients in a single grain of magnetite from the Bushveld Complex. *Mineral. Mag.* **47**, 27-34.
- DUNHAM, A.C. (1965): A new type of banding in ultra-

- basic rocks from central Rhum, Inverness-shire, Scotland. *Amer. Mineral.* **50**, 1410-1420.
- GOODE, A.D.T. (1976): Small scale primary cumulus igneous layering in the Kalka layered intrusion, Giles complex, central Australia. *J. Petrology* **17**, 379-397.
- HARKER, A. (1909): *The Natural History of Igneous Rocks*. Methuen, London.
- HAWKES, D.D. (1967): Order of abundant crystal nucleation in a natural magma. *Geol. Mag.* **104**, 473-486.
- HESS, G.B. (1972): Heat and mass transport during crystallization of the Stillwater igneous complex. *Geol. Soc. Amer. Mem.* **132**, 503-520.
- HUNTER, R.H. (1987): Textural equilibrium in layered igneous rocks. In *Origins of Igneous Layering* (I. Parsons, ed.). Reidel, Dordrecht, Holland.
- IRVINE, T.N. (1980a): Magmatic density currents and cumulus processes. *Amer. J. Sci.* **280A**, 1-58.
- _____ (1980b): Infiltration metasomatism, adcumulus growth, and double-diffusive fractional crystallization in the Muskox intrusion and other layered intrusions. In *Physics of Magmatic Processes* (R.B. Hargraves, ed.). Princeton Univ. Press, Princeton, New Jersey.
- _____ (1982): Terminology for layered intrusions. *J. Petrology* **23**, 127-162.
- _____ (1987): Layering and related structures in the Duke Island and Skaergaard intrusions: similarities, differences, and origins. In *Origins of Igneous Layering* (I. Parsons, ed.). Reidel, Dordrecht, Holland.
- JACKSON, E.D. (1961): Primary textures and mineral associations in the ultramafic zone of the Stillwater Complex. *U.S. Geol. Surv. Prof. Pap.* **358**.
- KANARIS-SOTIRIOU, R. (1974): Fine-scale layering in igneous intrusions: a possible mechanism for a non-depositional origin. *Geol. Mag.* **111**, 157-162.
- MAALØE, S. (1978): The origin of rhythmic layering. *Mineral. Mag.* **42**, 337-345.
- MCBIRNEY, A. & NOYES, R.M. (1979): Crystallization and layering of the Skaergaard intrusion. *J. Petrology* **20**, 487-554.
- MORSE, S.A. (1986): Convection in aid of adcumulus growth. *J. Petrology* **27**, 1183-1214.
- PETERSEN, J.S. (1985): Columnar-dendritic feldspars in the Lardalite intrusion, Oslo region, Norway: 1. Implications for unilateral solidification of a stagnant boundary layer. *J. Petrology* **26**, 223-252.
- TAIT, S.R., HUPPERT, H.E. & SPARKS, R.S.J. (1984): The role of compositional convection in the formation of adcumulate rocks. *Lithos* **17**, 139-146.
- THY, P. (1982): Titanomagnetite and ilmenite in the Fongen-Hyllingen basic complex, Norway. *Lithos* **15**, 1-16.
- _____ (1983): Cumulate chemistry and its bearing on the origin of layering: evidence from the Fongen-Hyllingen basic complex, Norway. *Tschermaks Mineral. Petrog. Mitt.* **32**, 1-24.
- _____ & ESBENSEN, K.H. (1982): Origin of certain small-scale igneous layering from the Fongen-Hyllingen basic complex, Norway. *Geol. Fören. Stockholm Forhänd.* **104**, 33-42.
- _____ & WILSON, J.R. (1980): Primary igneous load-cast deformation structures in the Fongen-Hyllingen layered basic intrusion, Trondheim region, Norway. *Geol. Mag.* **117**, 363-371.
- WAGER, L.R. (1959): Differing powers of crystal nucleation as a factor producing diversity in layered intrusions. *Geol. Mag.* **96**, 75-80.
- _____ (1963): The mechanism of adcumulus growth in the layered series of the Skaergaard intrusion. *Mineral. Soc. Amer. Spec. Pap.* **1**, 1-9.
- _____ & BROWN, G.M. (1968): *Layered Igneous Rocks*. Freeman, San Francisco.
- _____, BROWN, G.M. & WADSWORTH, W.J. (1960): Types of igneous cumulates. *J. Petrology* **1**, 73-85.
- WALKER, D., JUREWICZ, S. & WATSON, E.B. (1985): Experimental observation of an isothermal transition from orthocumulus to adcumulus texture. *Trans. Amer. Geophys. Union* **66**, 362 (abstr.).
- WILSON, J.R. & LARSEN, S.B. (1985): Two-dimensional study of a layered intrusion - the Hyllingen Series, Norway. *Geol. Mag.* **122**, 97-124.
- _____, ESBENSEN, K.H. & THY, P. (1981): Igneous petrology of the synorogenic Fongen-Hyllingen layered basic complex, south-central Scandinavian Caledonides. *J. Petrology* **22**, 584-627.

Received November 26, 1986; revised manuscript accepted June 30, 1987.