The origin of macrorhythmic units in the Lower Zone of the Lille Kufjord Intrusion, northern Norway

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The Lille Kufjord Intrusion is one of the youngest mafic plutons in the Seiland Magmatic Province which forms part of the Middle Allochthon of the North Norwegian Caledonides. It was emplaced at a mid-crustal level into Proterozoic, sillimanite-grade paragneisses during the Middle Cambrian, probably in an extensional tectonic regime. Caledonian deformation is locally penetrative in the envelope but the intrusion is little affected and retains its original form, orientation and synformal internal structure. The intrusion contains an up to 100m-thick Marginal Series (MS) and a circa 1400m-thick Layered Series. The latter is subdivided into a 270m-thick Upper Zone of modally-layered gabbronorite (plagioclase-clinopyroxene-orthopyroxene cumulates) and a 1130m-thick olivine-bearing Lower Zone. The upper 750m of the Lower Zone (LZb) consists exclusively of modally-layered olivine gabbro while the c. 380m-thick lower part (LZa) is composed of a sequence of cumulates of varied composition. The MS gabbronorites and olivine gabbronorites exhibit modal and textural layering which is subparallel to the steep walls of the pluton. Pockets and discontinuous bands of pegmatitic magnetite gabbronorite are conspicuous in the MS and some are cored by xenoliths of paragneiss or coarse-grained granitoid. The MS appears to have crystallized from differentiated and contaminated basalt magma flowing down the walls of the magma chamber. A detailed log of LZa has revealed 42 macrolayers. Macrolayers of olivine cumulate (oC), clinopyroxene-olivine cumulate (doC) and plagioclase-clinopyroxene-olivine cumulate (pdoC) are almost equal in numbers but pdoC dominates the sequence in total thickness, followed in importance by oC. Analysis of upward layer transitions shows that the LZa sequence exhibits strong first-order Markovian properties and this forms the rationale for subdivision into 16 macrorhythmic units of different types. The most common macrorhythmic unit consists of oC overlain successively by doC and pdoC. Uncompleted units comprise oC followed by doC. Reduced units have a basal doC macrolayer overlain by pdoC. In interrupted units oC is followed directly by pdoC. Logging of additional sections shows that the main features of the stratigraphic sequence persist along strike for up to 2.7km while there are lateral variations in the number of units and in the thicknesses and nature of individual macrorhythmic units. Some units appear to be lenticular and rest discordantly on underlying cumulates. Electron microprobe analysis of olivine in sequential samples from two typical macrorhythmic units reveals that the basal oC macrolayers contain the most magnesian olivines and that the bases of the units are regressive discontinuities. The LZa cumulates are deduced to have crystallized at the base of a stratified, surge-type magma chamber. Liquid layering was established and maintained by the periodic emplacement of hot, olivine-saturated basalt which underflowed the resident, more-differentiated magma. Primocrysts grew in the diffusive boundary layer at the top of the basal liquid layer and were transported to the floor of the chamber by two-phase convection. With sufficient time between emplacement events, minerals crystallized in the order olivine-clinopyroxene-plagioclase. As the layer evolved it mixed with overlying liquid layers when densities were equalized. If differentiation was terminated prematurely by emplacement of new magma, an uncompleted unit could be formed. Elevation of liquid layers due to the influx of magma resulted occasionally in liquid saturated in clinopyroxene and olivine overrunning part of the sloping magma-chamber floor, initiating a macrorhythmic unit of the reduced type. Macrorhythmic units of the interrupted type were formed when magma drained from the chamber into the underlying feeder. This led to the subsidence of the liquid layering, bringing differentiated magma to the floor of the chamber in place of olivine-saturated magma. The presence of high-temperature magma at the base of the chamber resulted in assimilation of the Marginal Series and it contains no record of the formation of LZa.

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Introduction

In recent years considerable advances have been made in the understanding of the physical processes which may take place in crustal magma chambers. In particular, the recognition of the importance of compositional versus thermal contributions to buoyancy has revolutionised views on convection and differentiation in large bodies of magma (Turner 1980, Chen & Turner 1980, Huppert & Sparks 1980, 1984). Theoretical considerations and experiment have led to a number of competing models for the way in which crystallization takes place in magma chambers as they evolve and cool (e.g. Turner & Campbell 1986, Clark et al. 1987, Martin et al. 1987, Weinstein et al. 1988, Martin & Nokes 1988, Marsh 1988, 1989). These models need to be tested against nature itself, either directly, for instance by observations carried out on lava lakes, or indirectly, through the study of lavas and pyroclastics derived from subsurface chambers and igneous intrusions which represent solidified magma chambers. Layered intrusions are particularly relevant since the sequences of rocks they contain present a stratigraphic record of transient events and processes which took place during the life span of the magma chambers in which they crystallized.

The observations presented here from the Lille Kufjord Intrusion and the deductions extracted from them are intended to be a contribution to the interpretation of layered igneous rocks in general, and the origin of macrorhythmic units in particular, as well as the reconstruction of ephemeral events in a particular magma chamber.

The Lille Kufjord Intrusion and its envelope

The Lille Kufjord Intrusion appears to be one of the youngest of the suite of mafic plutons which constitute a major part of the Seiland Magmatic Province (Roberts 1974). The latter is developed in the Sørøy Nappe, the uppermost tectonic unit of the Kalak Nappe Complex which constitutes the Middle Allochthon of the Northern Norwegian Caledonides (Roberts & Gee 1985). Interpretations of the plutonic history of the Seiland Magmatic Province have been presented by Robins & Gardner (1975) and more recently by Bennett et al. (1986). Due to data emerging from work on the isotope systematics of intrusions and their host rocks, ideas on the timing and nature of the evolution of the Seiland Province are presently undergoing radical revision (Aitcheson & Taylor 1989, Aitcheson et al. 1989). The results of these recent studies will, however, be presented elsewhere and the description in this section will focus only on geological relationships in the vicinity of the Lille Kufjord Intrusion which are relevant for evaluation of the environment of emplacement and crystallization of the pluton. In addition an account of the general characteristics of the intrusion is presented which supplements and in part supersedes the preliminary description of Robins & Gardner (1974). The Marginal Series of the Lille Kufjord Intrusion is described in some detail. It exhibits features which have important implications for the petrogenesis of the intrusion in general and the Lower Zone cumulates of the Layered Series in particular.

The intrusive environment: evidence from the envelope

The Lille Kufjord Intrusion is emplaced into high-grade paragneisses as well as the Olanes Gabbronorite (Plate 1). The paragneisses are well exposed on the headland between Store Kufjord and Lille Kufjord where continuous sections are available from rocks which bear only the imprint of regional metamorphism into the contact metamorphic aureole of the Lille Kufjord Intrusion. However, the narrow strip of paragneiss which separates the Lille Kufjord Intrusion and the Olanes Gabbronorite between Vardefjell and Olanes has been intensely metamorphosed in the aureoles of both intrusions. Additional, but discontinuous exposures of contact-metamorphosed paragneiss are present along the east coast of Lille Kufjord and on the eastern slopes of Lille Kufjorddalen.

The paragneisses are muscovite-free, predominantly quartzo-feldspathic rocks with ubiquitous garnet and generally with a pronounced compositional banding. The sedimentary parentage of the gneisses is demonstrated by the occurrence of narrow bands of quartzite and calc-silicate rocks. The protolith appears to have been a sequence of variably-calcareous, immature sandstones with subordinate beds of argillaceous sediment. Similar paragneisses are widely developed in the Seiland Magmatic Province and have been referred to informally as garnet gneiss by various authors (e.g. Hooper 1971). In the western parts of the province garnet gneiss is structurally overlain by a sequence of varied metasediments constituting the Sørøy Succession (Ramsay et al. 1985). The Sørøy Succession has been presumed to be Late Proterozoic to Middle Cambrian in age (Ramsay et al. 1985) but new isotopic data suggests that it was deposited entirely in the Late Proterozoic, before 800 Ma (Aitcheson et al. 1989). In addition the garnet gneiss is intruded by gabbros which have yielded Sm-Nd internal isochron ages of c. 600 Ma (Aitcheson 1989). Thus, the paragneisses hosting the Lille Kufjord Intrusion and the Olanes Gabbronorite are regarded at present as part of a Precambrian metamorphic complex.

The paragneisses show evidence of a complex structural evolution. At least two generations of folds affected the lithological banding prior to the emplacement of the Lille Kufjord Intrusion. Both generations of early folds are tight to isoclinal, similar folds associated with axial-planar foliations. Post-D1 mafic dykes (amphibolite) are common in the paragneisses and have either been folded by the younger generation of structures or undergone boudinage during their development, or both.

Distant from the contact of the Lille Kufjord Intrusion pelites and semipelites contain varying amounts of almandine garnet, biotite and sillimanite in addition to quartz, K-feldspar and plagioclase, indicating metamorphism in the upper part of the almandine amphibolite facies. Within about 400 m of the contact of the Lille Kufjord Intrusion biotite is less abundant and appears to have grown at the expense of distinctive contact-metamorphic assemblages including garnet, sillimanite, cordierite, hercynitic spinel and rutile. The less-aluminous metasandstones contain garnet, hypersthene, biotite and, less commonly, hercynitic spinel, in addition to quartz and feldspars. Hercynitic spinel is generally enclosed within garnet and sillimanite, suggesting that spinel and quartz co-existed at the highest temperatures attained during contact metamorphism (>770° Holdaway & Lee 1977, Vielzeuf 1983) and that the principal mineral assemblages developed as temperatures in the aureole waned. The compositions of co-existing garnet (mg# = 50.8) and cordierite (mg# = 88.6) suggest equilibration during cooling of the aureole rocks (to temperatures of 650-700°C) at a pressure between 5.4 and 8.2 kb, depending on P_{H_2O} (Martignole & Sisi 1981, Aranovich & Podlesskii 1983). A lithostatic pressure in the upper part of this range (corresponding to P_{H_2O} near to P_{total})is considered unrealistic. Conditions corresponding to the highest pressures indicated by the garnet-cordierite thermobarometer would place the equilibrium in the stability field for kyanite as determined by Holdaway (1971) rather than that for sillimanite. Furthermore, the common occurrence of graphite in the inner part of the Lille Kufjord aureole indicates that P_{H_2O} was substantially less than P_{total}.

Metamorphism in the contact aureole resulted in the partial to complete recrystallization of the foliated, quartz-free amphibolite dykes to granoblastic hornblende hornfelses. Recrystallization was restricted to the margins of the widest dykes, even in the inner part of the aureole, while narrow amphibolites typically are completely transformed.

Granitic neosomes are sporadically developed in metasandstones and metapelites throughout the contact-metamorphic aureole and may crosscut both the lithological banding in the paragneisses and the recrystallized amphibolites they enclose. In a zone up to about 15 m wide along the contact of the Lille Kufjord Intrusion the paragneisses are, however, distinctly migmatitic. Here, lithological banding in the paragneisses is less pronounced than elsewhere and a granodioritic neosome is abundant. Rheomorphic breccias are developed in places in this zone. They consist of blocks and slabs of paragneiss and mafic hornfels enclosed in massive or banded granodiorite and appear to have resulted from partial melting to a degree sufficient for disruption of the aureole rocks.

In places, rocks in the migmatitic zone are characterized by ellipsoidal segregations, typically a few cm long, consisting of granoblastic plagioclase (confirmed by electron microprobe analysis) intergrown with hercynitic spinel and lesser amounts of corundum. These lenticular bodies generally reside in a quartzofeldspathic matrix and in places are partly replaced by garnet. Their evolution is obscure but they appear to have developed within semipelitic protoliths, possibly by the high-temperature breakdown of garnet in the presence of anatectic melt. Although only a minor component, the occurrence of the aluminous lenticles in the innermost part of the contact-metamorphic aureole has important implications since identical bodies are exceedingly common as xenoliths throughout the Layered Series of the Lille Kufjord Intrusion. The mineralogical identity of the segregations in the aureole and xenoliths in the Lille Kufjord Intrusion appears to the authors to be important evidence for large-scale assimilation of country rocks during the emplacement and crystallization of the intrusion.

The northeastern part of the Lille Kufjord Intrusion is in discordant contact with the Olanes Gabbronorite between Store Kufjord and Nav'stuvag'gi. The Olanes Gabbronorite was both emplaced and deformed prior to the development of the Lille Kufjord Intrusion. It forms a sheet exhibiting a moderately to steeply-dipping foliation or modal layering or both. The thickness of the sheet increases from about 500 m near Olanes, where it consists of medium-grained, foliated and metamorphosed gabbronorite and pegmatitic, Fe-Ti oxide-rich gabbronorite, reaches a maximum of more than 1000 m on Saddugai'sa and decreases again further north where it crosses Lille Kufjorddalen. In its thickest portion the Olanes Gabbronorite contains modally-layered gabbronorite which alternates with thin layers of olivine gabbronorite (Oosterom 1956). Large blocks and rafts of paragneiss occur within the sheet and are particularly common between Saddugai'sa and Store Kufjord.

Magmatic events which postdated the crystallization of the Lille Kufjord Intrusion are represented by dykes of granitic pegmatite, blastoporphyritic amphibolite and syenite pegmatite, emplaced in that order, which cut both the intrusion and the rocks of the envelope. In addition, a single dyke of nepheline syenite pegmatite has been recorded within the Lille Kufjord Intrusion. The amphibolites are members of a regionally-developed swarm of metamorphosed picrite/ankaramite - alkali olivine basalt dykes (Robins & Takla 1979) which also cut the nearby Rognsund Intrusion (Robins 1982) as well as the Melkvann Ultramafic Complex (Bennett et al. 1986). Syenite pegmatites emplaced into the Lille Kufjord Intrusion are associated with narrow metasomatic aureoles. In the envelope, however, there are several zones in which the paragneisses have been transformed into alkali feldspar-ægirine augite-sphene-apatite fenites in connection with the intrusion of thin dykes of carbonatite. The most extensive of these zones appears to parallel the eastern contact of the Lille Kufjord Intrusion and extends northward from Skjåvikvatnet almost to the coast of Store Kufjord, a distance of about 1km. Further occurrences of fenite are found close to and subparallel with the southwest contact of the Lille Kufjord Intrusion on Store Kufjordnes. Fenitization in these zones overprinted fabrics related to the second generation of folds in the paragneiss, as well as contact-metamorphic mineral assemblages.

Deformation of the Lille Kufjord Intrusion is restricted to rare, narrow shear zones. In the paragneisses of the envelope, however, deformation postdating the crystallization of the intrusion was locally intense. Later deformation is most apparent in the fenitized rocks. On Store Kufjordnes these exhibit a tectonic foliation which in places is disposed around open to tight folds. In zones of intense deformation both fenites and adjacent unaltered paragneisses are reduced to thinly-banded mylonites. In the latter rocks quartz and feldspars are recrystallized to fine-grained, polygonal mosaics while biotite and garnet form small neoblasts. There is no evidence, however, of the regrowth of sillimanite. Elsewhere in the Seiland Magmatic Province, mineral assemblages developed in mafic dykes deformed together with alkaline igneous rocks suggest that the late deformation took place under upper greenschist- or lower amphibolite-facies metamorphic conditions (Sturt & Ramsay 1965, Ramsay & Sturt 1970, Robins 1974).

The field relationships summarized above have been interpreted in terms of the synorogenic emplacement of the Lille Kufjord Intrusion (e.g. Robins & Gardner 1974 & 1975). Recently-acquired isotopic data (Pedersen et al. 1988, Dallmeyer, 1988a & 1988b, Aitcheson et al. 1989) suggests, however, that the tectonothermal evolution of the Seiland Province was significantly more prolonged and complex than previously recognised. Instead of developing during the course of a single tectonic and metamorphic cycle (the Finnmarkian Orogeny) (Ramsay & Sturt 1986), the Seiland Province appears to have had a polyorogenic evolution (Aitcheson & Taylor 1989). The authors presently regard the Lille Kufjord Intrusion as having been emplaced in an anorogenic tectonic setting, possibly during an episode of crustal extension. Intrusion took place some considerable time after the principal orogenic deformation and metamorphism of the Sørøy Succession in the Late Proterozoic (>800 Ma) but before renewed orogenic activity in the Late Cambrian or Early Ordovician.

Isotopic constraints on the age of emplacement

An extremely-fresh gabbronorite from the Upper Zone of the cumulate sequence in the Lille Kufjord Intrusion has yielded a Sm-Nd internal isochron age of 488 ±57(2σ) Ma (Table 1 & Fig. 1) which is interpreted as the age of crystallization.

As noted above, crystallization of the Lille Kufjord Intrusion pre-dated alkaline magmatic activity in the Seiland Magmatic Province represented by the intrusion of syenite and nepheline syenite pegmatites and carbonatites and also the development of fenites. Large, euhedral zircons collected from nepheline syenite pegmatites, one from a swarm of dykes about 4 km northeast of the Lille Kufjord Intrusion, have yielded concordant, U-Pb ages of 531 ±2 and 523 ±2(2σ) Ma (Pedersen et al. 1988), suggesting that the alkaline rocks crystallized in mid-Cambrian times (Harland et al. 1982).

The Sm-Nd age suggests that the Lille Kufjord Intrusion is younger than the alkaline rocks but the age is relatively imprecise and has an uncertainty that overlaps the U-Pb ages obtained from the nepheline syenite pegmatites. On the basis of the isotopic data presently available it appears most probable that the Lille Kufjord Intrusion was emplaced in the Middle Cambrian.

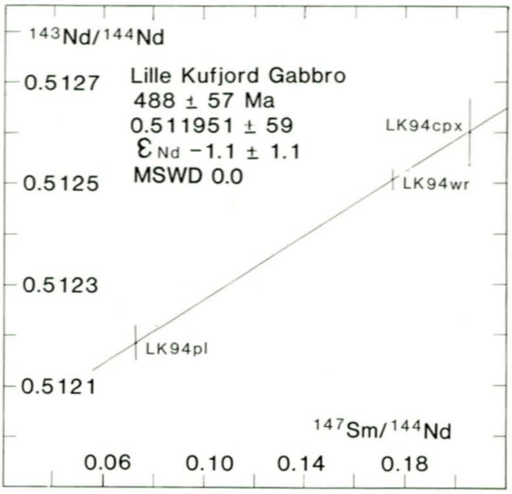

Fig. 1. Sm-Nd isochron plot of isotopic data presented in Table1.

Sample	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ±σ
LK94 pl	0.17	1.40	0.0729	0.512184±34
LK94 wr	0.95	3.29	0.1741	0.512508±20
LK94 cpx	0.29	0.87	0.2041	0.512601±68

pl = plagioclase separate (circa 97% pure).
wr = bulk-rock.
cpx= Ca-rich pyroxene separate (circa 90% pure).

Reproducibility of $^{147}Sm/^{144}Nd$ is 0.1%. Errors quoted for $^{143}Nd/^{144}$ Nd are for within-run precision, minimum reproducibility is estimated as ±20. Nd isotopic analyses were carried out in the Dept. of Geology, University College, Dublin. All samples were spiked and Sm-Nd concentrations and Nd isotopic analyses were obtained from the same dissolution. Procedures were similar to those of Menuge (1988) and Menuge & Daly (in press). Maximum chemical blanks were Nd = 1ng and no blank corrections were required. Mass spectrometry was carried out on a semi-automated VG Micromass 30. The value of $^{143}Nd/^{144}Nd$ obtained for the La Jolla standard was 0.511866.

Table 1. Sm-Nd mineral and whole-rock isotopic data from gabbronorite sample LK94.

Size, contact relations and shape of the intrusion

The Lille Kufjord Intrusion is a small layered pluton. With an elongated outcrop, 6 km long and a maximum width of 1.6 km on the northwest shore of Store Kufjord, it occupies a total area of only 6.5 km². Thus, the intrusion is an order of magnitude smaller than the layered mafic plutons of the Thulean Province, such as the Skærgaard Intrusion and the Rhum Intrusion, Scotland, both with outcrop areas of about 50 km².

The Lille Kufjord Intrusion is exposed to a height of 650 m, giving a minimum volume of approximately 4.2 km³ above sea level, assuming upward conservation of plan area. Accommodation of the 1370 m-thick Layered Series increases the minimum volume of the pluton to almost 9 km³. In view of the rather primitive composition of the uppermost of the cumulates preserved in the Layered Series, it seems probable that the total volume of the Lille Kufjord Intrusion was, however, substantially larger.

Contacts between the Lille Kufjord Intrusion and its envelope are everywhere steep. Around Altneset and on the headland between Store and Lille Kufjord contacts appear to be near vertical. The northeastern contact between Store Kufjord and Nav'stuvag'gi dips outwards at angles of around 70-80°, as does the south-

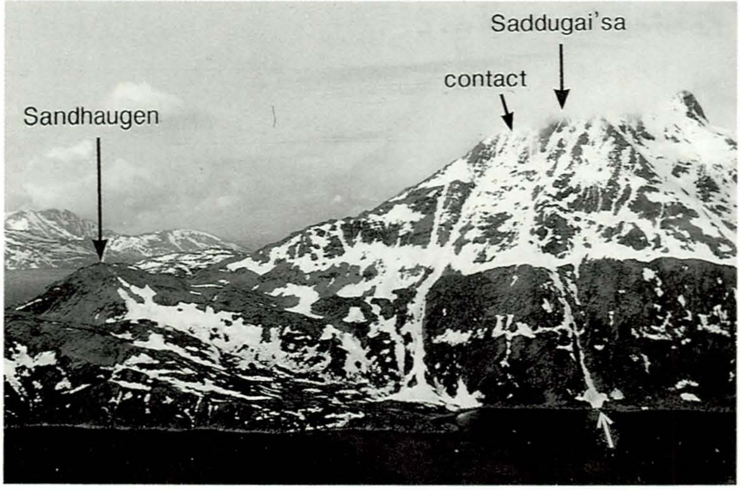

Fig. 2. View across Store Kufjord of the section through the Lille Kufjord Intrusion. Sandhaugen is located in the left middle ground and the top of Saddugai'sa is partly shrouded in mist on the right-hand side of the photograph. The contact between the Lille Kufjord Intrusion and the Olanes Gabbronorite dips steeply to the right (NE) and is followed by a marked, partly snow-filled gulley which can be followed from the coast to a point more than half way up the cliff face. Modal layering in the Lille Kufjord Intrusion, arranged in a gentle synform, can be picked out in the cliff between Sandhaugen and Saddugai'sa.

western contact where it runs close to the shore of Lille Kufjord. In plan view, the northeastern and southwestern contacts are subparallel over most of the outcrop. Beneath Store Kufjord and on Altneset, however, the contacts approach each other, producing a wedge-shaped outcrop pattern. The intrusion continues for a short distance to the south of Vardefjell as a 40 m broad dyke of gabbronorite. In contrast, the northern termination of the intrusion is rounded.

The southwestern contact is generally subconcordant with the principal foliation in the paragneisses of the envelope. The northeastern contact is, however, discordant along much of its length. On Altneset, paragneiss forms a screen between the Lille Kufjord Intrusion and the Olanes Gabbronorite which can be traced onto the outermost tip of Olaneset. On the western shore of Store Kufjord the screen is absent and northwestwards towards the south ridge of Saddugai'sa the Lille Kufjord Intrusion cuts into the Olanes Gabbronorite. The discordant nature of the contact is particularly clear in the cliffs on the west side of Store Kufjord which present a natural cross section some 700m high (Fig. 2). Here, the contact can be seen cutting obliquely across moderately-dipping modal layering in the Olanes Gabbronorite. In Nav'stuvag'gi the contact of the Lille Kufjord Intrusion again cuts through the lower boundary of the Olanes Gabbronorite and the resulting wedge of paragneiss increases in thickness northwards over the western ridge of Kufjordtind.

Relationships between the margins of the Lille Kufjord Intrusion and pre-existing structures indicate that both displacive and replacive mechanisms were of importance during emplacement. Deflection of the main foliation in the paragneisses around the northern termination of the intrusion is considered the result of cumulative dilation of the country rocks, almost certainly along a NE-SW trend. Most of the xenoliths within the intrusion are, however, believed to have resulted from the stoping of blocks of envelope rocks.

The form of the contacts suggests that the Lille Kufjord Intrusion widens somewhat in its extension below sea level (Plate 1, section A-B). Judging from the disposition of the modal layering in the Layered Series (see below), the root of the intrusion is situated beneath Store Kufjord. The exposure of the lowest stratigraphic levels of the Layered Series in the northwest corner of the intrusion, where the Marginal Series is thinnest, suggests that a floor is present at a relatively shallow level beneath this part of the intrusion. The subsurface part of the Lille Kufjord Intrusion is thus envisaged as generally dyke-like, closing at shallower depth in the north and continuing to deeper levels beneath Store Kufjord in a keel-like prolongation which may be continuous with a feeder dyke.

Structural relationships suggest that the upward continuation of the Lille Kufjord Intrusion must have been emplaced into the Olanes Gabbronorite. The occurrence of xenolithic material of metasedimentary parentage throug-

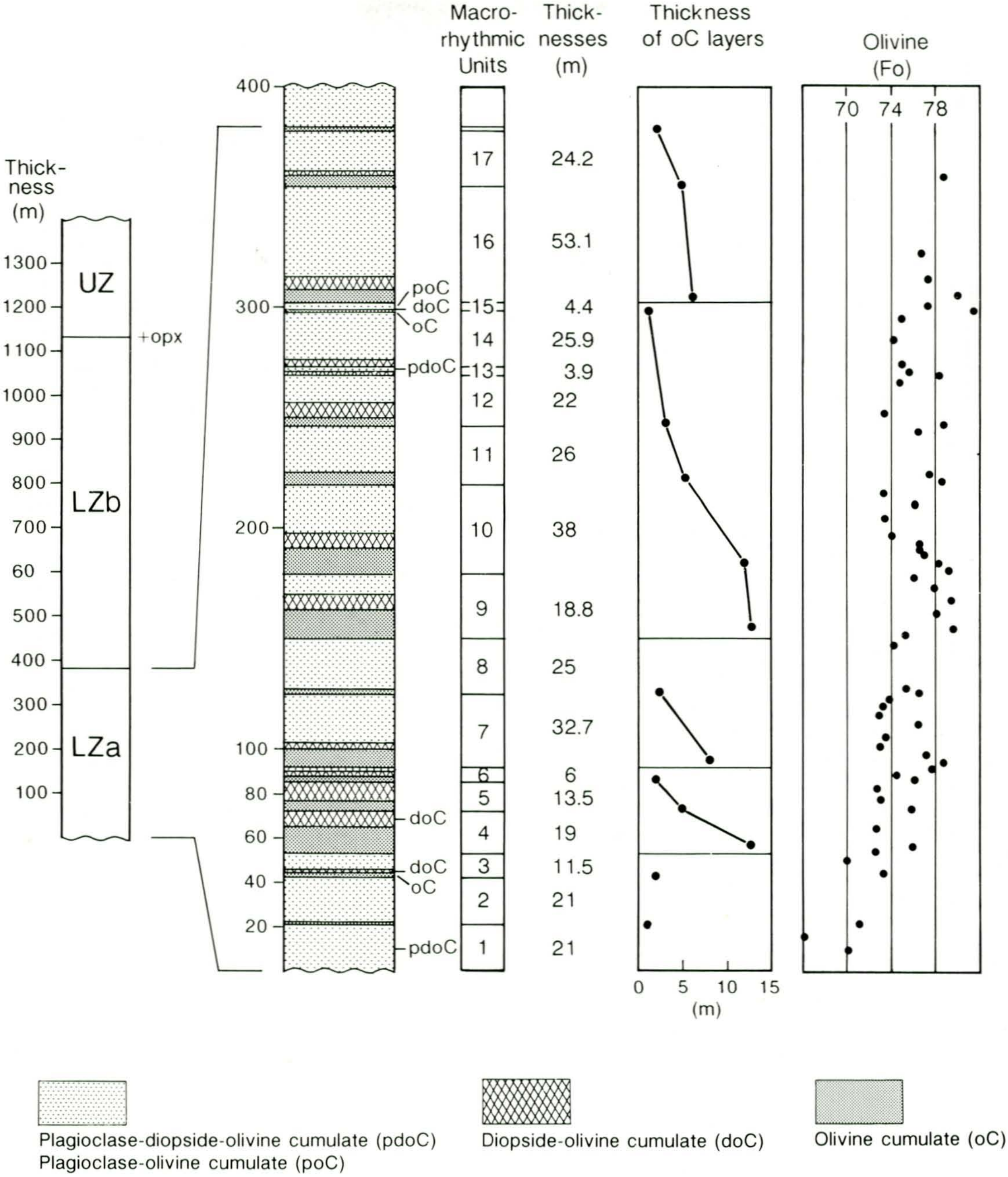

Fig. 3. The generalized stratigraphy of the Layered Series of the Lille Kufjord Intrusion (left-hand column) and the sequence of Lower Zone a cumulates as revealed by by logging along traverse B (Plate 1). The subdivision of the sequence of 42 macrolayers into 17 macrorhythmic units is presented together with the thicknesses of the individual units. The stratigraphic variation in the thicknesses of macrolayers of olivine cumulate (oC) in traverse B is plotted alongside the data for the macrorhythmic units and appears to form a rhythmic pattern. The right-hand column shows the stratigraphic variation in olivine composition in the various cumulate types. Note that there is a pronounced trend towards more magnesian olivines upwards through the lower part of LZa.

hout the preserved part of the Layered Series may, however, indicate that the roof of the intrusion was emplaced into paragneisses structurally above the Olanes sheet. Although the original vertical dimensions of the intrusion can hardly be constrained with any degree of certainty, it seems at least likely that it was considerable and similar in magnitude to its horizontal length.

Internal subdivision and structure

The rocks of the Lille Kufjord Intrusion can be subdivided into two petrographically, structurally and genetically different series (Robins & Gardner 1974): The Marginal Series consists principally of medium-grained to pegmatitic gabbronorites (±olivine) which line the external contacts of the intrusion; The Layered Series constitutes the major part of the intrusion and consists of a variety of cumulates which are in sharp, discordant contact with the Marginal Series rocks (Plate 1). The Layered Series can be subdivided into a 1130 m-thick Lower Zone consisting of feldspathic peridotite, olivine clinopyroxenite and olivine gabbro, i.e. cumulates in which cumulus olivine is ubiquitous and Ca-poor pyroxene has exclusively postcumulus status, and a c. 250 m-thick Upper Zone characterized by more evolved, gabbronoritic cumulates containing cumulus Ca-poor pyroxene. The boundary between the Lower and Upper Zones has been mapped at the base of the stratigraphically-lowest cumulates containing cumulus orthopyroxene. For convenience of description the Lower Zone has been further subdivided into two subzones (LZa and LZb). The uppermost subzone (LZb) is c. 750 m thick and consists almost exclusively of modally-layered olivine gabbro. In contrast, the 380 m-thick LZa contains a variety of distinctive types of cumulate (Fig. 3), including layers of feldspathic peridotite (olivine cumulate, oC), olivine clinopyroxenite (diopside-olivine cumulate, doC) and rare troctolite (plagioclase-olivine cumulate, poC), in addition to olivine gabbro (plagioclase-diopside-olivine cumulate, pdoC). The boundary between the subzones is placed at the top of the stratigraphically-uppermost peridotite layer.

The Marginal Series

The distinctive rocks forming the Marginal Series appear to be present along all parts of the external contact of the Lille Kufjord Intrusion with the exception of its southeastern prolongation. They are relatively susceptible to weathering and exposures in many places are fragmentary. The coast on Store Kufjordnes presents a continuous section through the series and reasonably complete sections are also available on Altneset and beside the ferry quay north of Rognsund School. The Marginal Series can be traced continuously over the peninsula between Store Kufjord and Lille Kufjord. Exposures of the series further to the northwest, close to the shore of Lille Kufjord, are small and isolated but sufficient to demonstrate continuity. The Marginal Series is exposed in cliffs above Lille Kufjorddalen, but rather difficult of access, and due to extensive development of scree, exposures of the series along the northeastern contact of the Lille Kufjord Intrusion between the western ridge of Kufjordtind and Store Kufjord are rare.

The thickness of the Marginal Series varies considerably. The series attains its maximum development on the peninsula between Store and Lille Kufjord where it is around 100m thick (104m on the shore of Kufjordnes). Here the Marginal Series is sandwiched between paragneisses of the envelope and LZb olivine gabbros. When traced to the northwest, where it borders cumulates progressively lower in the Layered Series, the thickness of the Marginal Series gradually decreases to a minimum of 10-20 m. On Altneset and north of Rognsund School the Marginal Series is about 100 m thick. When followed to the southeast the series along both contacts thins and eventually wedges out. In the most distal part of the intrusion, south of Vardefjellet, LZb olivine gabbros are in direct contact with the country rocks and pass rapidly into gabbronorite of the dyke-like termination.

The outermost 2-5m of the Marginal Series in the Kufjordnes section and on Altneset is composed of massive gabbronorite. The latter is medium to coarse grained, granular or ophitic and characterized by numerous blocks and rafts of highly metamorphosed paragneiss, the sporadic presence of quartz and up to fist-sized garnet crystals. Fine-grained rocks which could be interpreted as representing chilled magma have not been found along the contact of the Lille Kufjord Intrusion. The external contact of the Marginal Series is in fact poorly defined in the field and there appears to be a fairly rapid transition over about 50 cm from the migmatites of the innermost part of the contact-metamorphic aureole into the hybrid rocks of the outermost part of the Marginal Series.

The outermost, massive gabbronorite passes inwards into heterogeneous, medium-grained to pegmatitic olivine gabbronorite and gabbronorite which form the remainder of the Marginal Series. This zone resembles in several ways the banded division of the Skaergaard Marginal Border Series as described by Wager & Deer (1939). It is characterized by a more or less pronounced layering defined by variations in grain size and modal composition as well as the common occurrence of elongated pockets and bands of pegmatitic magnetite-ilmenite gabbronorite. The latter, although present in subordinate amounts, is the most distinctive rock type in the Marginal Series. Nowhere in the series have rock types equivalent to the olivine- and pyroxene-rich layers in LZa of the Layered Series been observed. Their absence must have important implications for the genetic relationship between the Marginal and Layered Series.

Layering in the Marginal Series generally has a steep dip and is subparallel with the external contact of the intrusion. In vertical exposures, layers are tabular or gently undulating. In certain near-horizontal surfaces on the peninsula between Store Kufjord and Lille Kufjord the layering is corrugated and arranged in a series of arcs, convex towards the interior of the intrusion, which meet in angular cusps 2-3m apart. In these instances it appears that the corrugations of the layering plunge steeply in the plane of the layering. Layering of this type occurs in the Marginal Border Series of the Skærgaard Intrusion and has been described as colloform (McBirney & Noyes 1979, Irvine 1982). In a single place in the Kufjordnes section discontinuous bands of pegmatitic gabbronorite are arranged in a trough-like structure (Fig. 4) which also plunges steeply down the general plane of the layering in adjacent rocks. The colloform layering and the trough suggest the operation of oscillatory crystallization of magma moving upwards or downwards along the temporary margin of the chamber.

The gabbronorite pegmatites exhibit a variety of forms. Many are tabular bodies with thicknesses of a few centimetres to several decimetres which may persist for many meters both laterally and down-dip. Others form strings of lenses parallel with the layering in the adjacent rocks. Isolated pods of pegmatite, elongated in the layering or with crudely-triangular and irregular shapes are also not uncommon. The margins of the pegmatites are fairly sharp but generally there is textural continuity with the surrounding rocks. Tabular pegmatites and individual lenses forming strings are consistently asymmetrical in that their sides closest to the margins of the intrusion are feldspar-rich. Plagioclase crystals commonly exhibit a statistical orientation forming a large angle with the margins of the pegmatites and are in subophitic intergrowth with pyroxenes and Fe-Ti oxides on the side towards the interior of the intrusion. Not uncommonly, the plagioclase crystals broaden away from the outer margin of the pegmatites. The structure of the pods of pegmatite is in most respects similar to that of the layers. They have feldspar-rich margins, the plagioclases appearing to have grown inwards. Several instances have been noted, however, of pockets of gabbronorite pegmatite with cores of coarse-grained granitic rocks (Fig. 5), some of which contain crystals of orthopyroxene and garnet. In a few cases the granitic material is closely associated with banded quartzo-feldspathic rocks similar to those of the country rocks. These occurrences suggest that the pegmatites crystallized from hybrid magmas generated by the assimilation of xenoliths derived from the metasedimentary rocks of the envelope. This inference

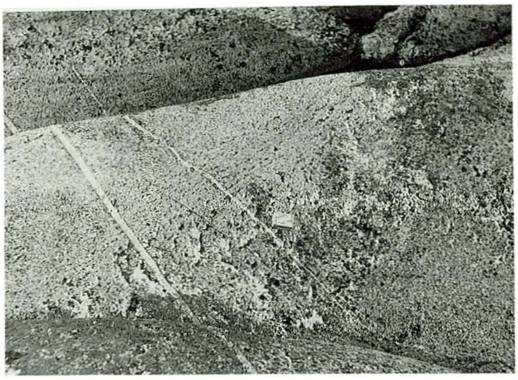

Fig. 4. A shallow, steeply-plunging trough defined by thin, discontinuous bands of gabbronorite pegmatite in the outer part of the Marginal Series olivine gabbronorite exposed on Store Kufjordnes. The darker appearance of the rocks in the foreground and right side of the outcrop is due to lichen cover. The Marginal Series here is cut by narrow granitoid and syenite dykes.

is supported by the presence of quartz and garnet in some pegmatites which lack granitic cores.

The field relationships of the pegmatites as outlined above are in most respects identical to similar pegmatites in the Skaergaard Marginal Border Series. Wager & Deer (1939) viewed the granophyric cores present in some of these pegmatites as the fused remains of partly digested xenoliths of gneiss and this interpretation has found support in a later, detailed study (Kays et al. 1981). However, Irvine (1987) regarded this mode of origin as inconsistent with field relations and suggested that the pegmatites resulted from the recrystallization or melting of pre-existing gabbroic rocks, possibly as a result of the ingress of water from the country rocks. For the pegmatites in the Lille Kufjord Marginal Series the present authors regard Wager & Deers (1939) deductions as entirely satisfactory. Layers of pegmatite are envisaged as having crystallized from hybrid magmas resulting from assimilation of xenoliths of paragneiss by magma flowing down the temporary walls of the magma chamber. The pegmatitic textures are viewed as a consequence of lower solidus temperatures and hence delayed crystallization of the hybrids compared with the uncontaminated magma.

Olivine and pyroxene appear to have lower mg numbers (mg#) in the rocks of the Marginal Series than in the cumulates of the Layered Series with which they are in contact. This is illustrated by the compositions of minerals as determined in the Kufjordnes section through the Marginal Series compared with those in LZ cumulates (Table 2). In addition, as noted above, layers of single-phase and two-phase cumulates present in LZa have no equivalents in the Marginal Series. It would appear reasonable to conclude that the Marginal Series and the Lower Zone of the Layered Series crystallized from compositionally-different magmas. The association in the Marginal Series of relatively iron-rich mafics and plagioclases of variable, and in some samples notably calcic composition (Table 2) is consistent with crystallization from hybrid magmas which resulted from variable amounts of assimilation of country-rock paragneiss.

The Layered Series. The 1380m-thick sequence of cumulates constituting the Layered Series occupies the major part of the Lille Kufjord Intrusion. LZ cumulates crop out over the majority of the area while UZ cumulates are restricted to the upper slopes of Saddugai'sa. The stratigraphically-lowest cumulates forming LZa occur within a roughly-triangular area in the northwestern part of the intrusion. They are well exposed in a series of bluffs and cliffs accessible from steep screes. Much of the outcrop of the LZb olivine gabbros is scree-covered but almost continuous sections are present on the south side of Nav'stuvag'gi and on the southwestern ridge of Saddugai'sa. Outcrops of LZb on Altneset are small and isolated and the topography here is subdued. The shores of Store Kufjord present, however, useful traverses across the intrusion within LZb cumulates which illustrate well the disposition of the layering in the southeastern part of the intrusion.

The Layered Series is in sharp, discordant contact with the rocks of the Marginal Series. The contact itself is subparallel with the layering in the Marginal Series. In the southeastern part of the intrusion the fabric in the Layered Series dips away from the contact at angles of 10-30°, the angle of dip gradually decreasing toward the interior of the intrusion. Thus, on both shores of Store Kufjord the layering in LZb is disposed in a gentle, symmetrical and upright syncline. The syncline becomes assymmetrical to the northwest as the axial trace curves towards the northeastern contact. The axial surface of the syncline is cut off at the Layered Series-Marginal Series contact to the south of Nav'stuvag'gi and in the latter the cumulates dip exclusively to the northeast, though at decreasing angles upwards in the cumulate stratigraphy and towards the northeastern contact of the intrusion. Thus in Nav'stuvag'gi the dip deceases from around 70° nearest Lille Kufjord to about 30° close to the northeastern limit of the Layered Series.

The syncline defined by the layering in the Layered Series has no counterpart in either the northeastern contact of the Lille Kufjord Intrusion or in the surrounding country rocks. It would appear, therefore, to be a result of processes which operated during the formation of the cumulate sequence. Robins & Gardner (1974) suggested that the latter crystallized in a magma chamber which rotated as a consequence of active, large-scale folding of the surrounding rocks. This explanation is now considered to be implausible since LZb cumulates

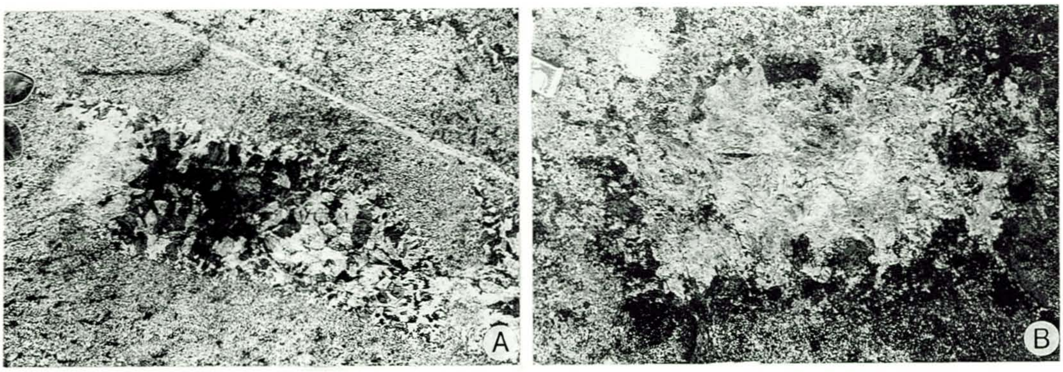

Fig. 5. Gabbronorite pegmatite in the Marginal Series. A) An elongated patch of pegmatite exhibiting the common structure of a plagioclase-rich marginal zone and a pyroxene-enriched interior. B) Gabbronorite pegmatite cored by granitoid pegmatite probably derived by melting of a xenolith of paragneiss.

in the northern part of the intrusion are homoclinal while layering in the same sequence further southeast is synclinal. The synclinal disposition of the layering and the association of the steepest dips of the layering with the oldest cumulates is now believed to have resulted from subsidence which took place simultaneously with the formation of cumulates constituting the Layered Series on the floor of the magma chamber. A likely mechanism for such subsidence is compaction and textural modification of cumulus crystals in the presence of interstitial melt. If this was the case then the axial trace of the syncline marks the location of the thickest accumulations of layered rocks while the plunge of the axial trace towards a nadir beneath Store Kufjord suggests that it is in this region that the intrusion has its roots. Furthermore, the axial surface of the syncline may have an important significance for the accumulation of the Layered Series itself, since it may trace out the successive positions of a basinal axis in the advancing floor of the magma chamber (cf. Robins et al. 1987). In addition, the vertical disposition of the axial surface of the syncline demonstrates that the Lille Kufjord Intrusion has retained its original orientation, despite later deformation and tectonic transport as part of the Sørøy Nappe.

	Plagioclase An	Clinopyroxene mg#	Orthopyroxene mg#	Olivine Fo
Upper Zone (UZ)	63 - 57	84 - 77	77 - 68	73 - 72
Lower Zone (LZa, LZb)	76 - 64	87 - 79	intercum.	82 - 66*
Marginal Series (MS)	83 - 59	80 - 71	69 - 66	62 - 60

mg# = 100Mg/Mg+Fe.
* Fo 72 - 70 in LZb
Fo 71 - 66 in lowest part of LZa

Table 2. Summary of mineral compositions in the major subdivisions of the Lille Kufjord Intrusion.

An analogue to the cross-bedded belt developed throughout a considerable stratigraphic thickness along the margins of the Skaergaard Layered Series (Irvine 1987) is absent along the shore sections of Store Kufjord. In the cliffs above Lille Kufjorddalen, however, olivine gabbros exhibiting cross-bedded small-scale modal layering are found in contact with the Marginal Series which crystallized along the steep, northern contact of the intrusion with the country rocks (Plate 1). Mapping suggests that the olivine gabbros are LZb cumulates and inspection of oblique aerial photographs has shown that the lateral extent of the cross-bedded belt is < 10 m. Due to the inaccessibility of most of these cliffs the vertical development of the cross-bedded rocks has not been determined. In the rare places where the inner contact of the Marginal Series is exposed near the shore of Lille Kufjord, no cross-bedded rocks intervene between the Marginal Series and LZa cumulates.

Xenoliths — distribution and derivation

Xenoliths are dispersed throughout the exposed part of the Layered Series. They are of three principal, petrographic types. Most common are small aluminous xenoliths composed principally of calcic plagioclase accompanied by small amounts of hercynitic spinel and, in some cases, accessory amounts of corundum. Xenoliths of olivine gabbro or troctolite are less common, but larger than the aluminous xenoliths. Large, rounded blocks of pegmatitic gabbronorite constitute an additional suite of distinctive, but relatively uncommon xenoliths.

The aluminous xenoliths are ubiquitous in the Layered Series. They are generally less than 5 cm long, ellipsoidal in form, granular in texture and exhibit a concentric internal structure with a dark, spinel-bearing core and a light, spinel-poor rim. Almost invariably they are orientated subparallel to layer boundaries and planar mineral laminations and in outcrops of homogeneous cumulates they accentuate the cumulus fabric. The aluminous xenoliths generally occur as dispersed individuals but can be concentrated along particular horizons and in places they occur in large clusters of irregular shape (Fig. 6). Although they are to be found in all types of cumulate the xenoliths in modally-layered sequences of olivine gabbro are concentrated in plagioclase-rich layers and the upper, plagioclase-enriched parts of modally-graded layers.

As noted above, segregations which are similar to the aluminous xenoliths in form and modal composition can be found in the innermost part of the contact-metamorphic aureole. This suggests that the xenoliths were derived from the paragneisses surrounding the Lille Kufjord magma chamber. It is believed that the aluminous enclaves were released into the chamber by assimilation of the less-refractory portions of the paragneisses.

Xenoliths of olivine gabbro and troctolite occur sporadically in the Lille Kufjord Intrusion. They appear to be most common near the bases of layers of olivine cumulate. They vary in shape from rounded, subspherical blocks to angular slabs. The blocks are generally from 5 to 30 cm in diameter but the slabs can be up to several metres long. Where enclosed in olivine cumulate the xenoliths commonly have irregular boundaries which impart a motheaten appearance. In places they are separated from the host feldspathic peridotite by cm-thick rinds of olivine pyroxenite.

Fig. 6. Isolated and clusters of lenticular plagioclase-spinel-corundum xenoliths within a macrolayer of olivine cumulate encountered in traverse A (Plate 1). Note the general orientation of the elongated xenoliths parallel with layer boundaries. Xenoliths are concentrated in this layer to an unusual degree. The tape-measure stretched over the outcrop is 12mm wide.

The textures of the olivine gabbro or troctolitic inclusions in olivine cumulate resemble those of the gabbroic cumulates elsewhere in the LZa sequence. They are regarded as autoliths, either torn up from the temporary floor of the magma chamber during periods when magma was flowing into it, or derived from the Marginal Series as a result of thermochemical erosion.

The most notable xenoliths of gabbronorite pegmatite occur as large, rounded blocks. The largest xenolith of this type which has been noted measured circa 4 m across and is enclosed in the upper part of the LZa sequence to the south of Nav'stuvag'gi. Further examples occur on the shores of Store Kufjord within LZb cumulates. Several of these blocks have cm-thick gabbroic rims which are coarser grained and more melanocratic than the enveloping cumulates. Smaller, rounded fragments of coarse-grained to pegmatitic gabbronorite are not uncommon within olivine and clinopyroxene-olivine cumulates of LZa. Some have serrated margins suggestive of assimilation.

Although they resemble the pegmatitic gabbro pods in the Skærgaard Intrusion which Irvine (1987) suggests were formed by the in situ recrystallization or remelting of cumulates, the gabbronoritic inclusions are believed to have been derived from the Marginal Series of the Lille Kufjord Intrusion. The gabbronorite inclusions are modally and texturally indistinguishable from the gabbronorite pegmatites which constitute such a distinctive part of the Marginal Series and there seems to be no reason to postulate any other, more exotic, origin. It is likely that periodic thermo-chemical erosion of the Marginal Series which lined the lower parts of the walls of the magma chamber (see below) led to local instability, avalanching and transport of blocks of Marginal Series rocks to the floor.

Stratigraphic relationships in Lower Zone a

The remainder of this contribution focuses attention on those features of the stratigraphically-lowermost cumulates exposed in the Lille Kufjord Intrusion which are pertinent for modelling of their origin. This section deals principally with stratigraphic relationships of the varied cumulates present in LZa. A statistical analysis of the sequence of macrolayers logged in a traverse through the whole of the exposed part of LZa forms the basis of a discussion of the rationale for its subdivision into macrorhythmic units. This one-dimensional treatment is then extended as far as is possible into two dimensions by comparison of sequences of macrolayers as logged in further, spaced traverses through parts of LZa. Finally, the one-dimensional systematics of layer thicknesses are used in a preliminary reconstruction of the sequence of events which took place in the Lille Kufjord magma chamber.

Types of cumulate

The principal types of cumulate forming LZa are olivine cumulate (oC), clinopyroxene-olivine cumulate (doC) and plagioclase-clinopyroxene-olivine cumulate (pdoC). In addition, there are minor occurrences of plagioclase-olivine cumulate (poC). The main rock types corresponding to these cumulates are as follows:

oC - Olivine melagabbro/plagioclase-bearing peridotite;
doC - Plagioclase-bearing olivine-hornblende clinopyroxenite or websterite;
pdoC - Olivine gabbro/olivine gabbronorite;
poC - (Leuco) troctolite/olivine leucogabbro.

The different cumulates are medium or coarse grained and their identification in the field is relatively unproblematical. The principal petrographic features of the cumulates are summarized below.

Olivine cumulates are characterized by yellowish-brown weathered surfaces. They contain 50-60 vol.% of anhedral to euhedral, slightly- to strongly-serpentinized olivine crystals up to 3 cm across which are enclosed in pyroxene, hornblende and plagioclase. Olivine crystals at any particular horizon within thick layers of oC are fairly uniform both in size and habit. Systematic decreases in the size of olivines have, however, been observed from the bases to the tops of several of the layers of oC present in LZa. The largest olivines are generally equant and there is an increasing tendency to elongation as the size of the crystals decreases. Columnar olivines are generally laminated and impart a crude fissility to the rocks. A macroscopic, statistical alignment of prismatic olivines has also been noted on some surfaces parallel to the mineral lamination but does not seem to be a particularly widespread feature of the olivine cumulates. Where observed, the lineation defined by olivine crystals plunges steeply in the plane of the modal layering towards the axis of the intrusion.

Pyroxene, hornblende and plagioclase form oikocrysts up to 10 cm across. In many sections at right angles to the olivine lamination (and layer boundaries) the oikocrysts are crudely elliptical and elongated subparallel to the lamination. On adjacent surfaces parallel to the lamination they exhibit no systematic elongation. This feature suggests less-constrained growth of postcumulus crystals along the plane of the olivine fabric than across it. Ca-rich pyroxene and hornblende generally envelop euhedral crystals of olivine. In orthopyroxene, however, olivines are anhedral, suggesting an olivine-pore magma reaction relationship. Ca-rich pyroxene is to varying degrees replaced by amphibole which appears to have crystallized last of the postcumulus minerals.

Pyroxene-spinel coronas are typically developed along grain boundaries between olivine and plagioclase. These normally consist of an inner zone of orthopyroxene adjacent to olivine and an outer symplectitic rim consisting of Ca-rich pyroxene, Ca-poor pyroxene and spinel. The coronas are interpreted as due to reaction between olivine and plagioclase during subsolidus cooling of the cumulates (Gardner & Robins 1974). They support the evidence from the contact-metamorphic aureole suggesting crystallization of the Lille Kufjord Intrusion at considerable depth in the crust.

Olivine cumulates contain minor amounts of sulphides in addition to silicate minerals. They occur in drop-like composite grains containing, in order of decreasing abundance, pyrrhotite, chalcopyrite and pentlandite, which probably represent an immiscible sulphide liquid.

Clinopyroxene-olivine cumulates are generally massive, greyish black and medium-grained to coarse-grained rocks consisting predominantly of Ca-rich pyroxene and hornblende with lesser amounts of olivine and plagioclase and minor quantities of sulphides. On weathered surfaces they exhibit a reddish-brown colour. Clinopyroxene in these cumulates occurs as anhedral to subhedral, equant crystals with diameters of 3-20 mm containing thin lamellae of exsolved orthopyroxene parallel to (100) and hercynitic spinel. It has been partially replaced by hornblende which otherwise forms oikocrysts enveloping both clinopyroxene and olivine. The latter forms anhedral to euhedral crystals usually smaller in size than in oC.

In the field, the postcumulus hornblende, orthopyroxene and plagioclase in doC are by no means obviously poikilitic. This is to a certain extent a result of the relatively small size of the indvidual oikocrysts but these minerals also appear to contribute less to the modal composition of doC than oC.

Plagioclase-clinopyroxene-olivine cumulates vary considerably in modal composition. The most mafic varieties are olivine melagabbros and generally occur in the basal parts of thick layers of pdoC. Olivine-poor leucogabbros form the upper parts of several of the pdoC layers present in LZa. Regardless of proportion, plagioclase occurs as laths up to 15 mm long which define a more or less distinct lamination. Plagioclase typically exhibits normally-zoned margins. Ca-rich pyroxene forms anhedral, equant or elongated cumulus crystals which may be continuous with surrounding poikilitic clinopyroxene. In some samples, elongated Ca-rich pyroxenes contribute to the mineral lamination. Olivine generally occurs as anhedra, either enclosed in oikocrysts of orthopyroxene which also enclose neighbouring crystals of plagioclase and clinopyroxene or separated in places from plagioclase by pyroxene-spinel coronas. Where orthopyroxene oikocrysts are narrow, a subophitic intergrowth between olivine and plagioclase can be detected. Olivine is absent in certain samples but its former presence is demonstrated by pyroxene-spinel symplectites or orthopyroxene-magnetite symplectites.

Of the major minerals only orthopyroxene is exclusively poikilitic. Hornblende, while clearly postcumulus, occurs mainly as granular rims to clinopyroxene or interstitial Fe-Ti oxides and is not as important a constituent as in doC or oC. The abundance of rounded grains of sulphide is also very much reduced in pdoC as compared to both doC and oC.

Plagioclase-olivine cumulates are rare in LZa. They are medium- to coarse-grained, leucocratic rocks resembling the more felsic varieties of pdoC. They contain laminated lath-shaped plagioclase crystals and anhedral olivine both of which may be enclosed in sporadic oikocrysts of Ca-rich pyroxene (Robins 1982).

Layers and macrolayers

Stratigraphic analysis, the results of which are reported below, was based on observations along traverses. The longest traverse (traverse B, Plate 1), of necessity a composite of several shorter traverses, extended from the lowest exposed horizon of the Lower Zone to the base of LZb. Observations along this and the other traverses were related directly to stratigraphic height by stretching a tape measure over successive exposures at right angles both to the strike and to the dip of the layering. This simple procedure was possible because the layers dip at steep to moderate angles in opposition to the surface slopes.

During logging along the different traverses through LZa it was impractical to record each of the thousands of layers which could have been recognized on the basis of their distinctive compositional and/or textural properties. Instead, logging concentrated on the delineation of distinctive stratigraphic units. Some of these units could have been referred to simply as layers, others as groups (of layers) but we have chosen to refer to them all as macrolayers.

Since the stratigraphic organization of the macrolayers which have been recognized in the logged sections is the main subject of the following one-dimensional statistical treatment and its subsequent extension into two-dimensional space, a definition of macrolayers is pertinent even though most petrologists conversant with layered intrusions will be familiar with the concept and its application in the subdivision of layered series. Macrolayers are defined as sheet-like entities characterized by the persistent occurrence of either a single cumulus mineral or a particular assemblage of cumulus minerals. They are bounded, therefore, by phase contacts (Jackson 1967).

The types of macrolayers recognized in the Lille Kufjord Intrusion correspond to the different types of cumulate represented in the Lower Zone. Thus, there are macrolayers of oC, doC, pdoC and poC. Macrolayers characterized by two or more cumulus minerals are, however, invariably composed of individual thin (<5 cm) to medium-thick (5 cm-1 m) layers which vary in their modal or textural characteristics (see below). It is essentially this difference in scale that has led to the introduction of the term macrolayer. Macrolayers recognized intraverse B themselves vary in thickness, however, from as little as 30 cm to as much as 23 m. Thus, the status assigned to relatively thin layers of oC during logging of sequences consisting of alternations of thinner layers of doC and oC was to some extent subjective. This problem is a common one in the subdivision of sequences of layered igneous rocks. In the Eastern Layered Series of the Rhum intrusion, for instance, thick layers of olivine cumulate alternate with sequences which consist predominately of allivalite (mainly troctolite) but commonly also contain subsidiary layers of peridotite (Faithfull 1985, Butcher et al. 1985). The number of subjective decisions of the type outlined above during logging of the traverses through the LZa of the Lille Kufjord Intrusion was limited and the resulting uncertainties are expected to have little significance for the stratigraphical analysis.

In the 380 m-thick sequence of LZa cumulates logged along traverse B, 42 macrolayers were identified (Fig. 3). Each of the principal types of macrolayer are almost equally represented in numbers, but not in thickness. Of the 42 macrolayers, 14 consist of pdoC and have a cumulative thickness of >224 m, corresponding to c. 63% of the section. A further 14 consist of oC and have a total thickness of 77.5 m, equivalent to c. 22% of the section. 13 macrolayers characterized by cumulus pyroxene and olivine comprise 55 m, or c. 15% of the sequence. Only a single macrolayer of poC, 1.1 m thick (equivalent to c. 0.3% of the section), was encountered in the traverse, at a stratigraphic height of 300 m.

Layer sequences and macrorhythmic units

A common procedure in layered intrusions with complicated sequences of cumulates has been the subjective grouping of macrolayers into cyclic (or megacyclic) units, i.e. sequences of macrolayers which are repeated through the stratigraphy in a regular manner. Subdivision is normally undertaken for the combined purposes of ease of description and genetic modelling. The usual assumption in this type of subdivision of layered sequences is that the repeated succession(s) of macrolayers primarily reflect the order(s) of crystallization of minerals from the parent magma(s). The different crystallization orders which may be predicted from experimental phase relations of synthetic basic and ultrabasic magmas and the corresponding sequence of cumulates expected from ideal fractional crystallization, as systematized by Irvine (1970), have been particularly influential in this respect. Recent studies have, however, focused attention on the probable significance of other processes in magma chambers in the formation of layer sequences, e.g. processes related to composition-density effects, mixing of disparate magmas and assimilation. Furthermore, many of the peridotites traditionally regarded as basal layers in repeated cyclic units in the Rhum Intrusion have been re-interpreted as later sill intrusions (Bédard et al. 1988, Renner & Palacz 1987).

In view of the current debate on the origin of cumulates, the present authors regard the application of more objective methods of analysis to layered sequences as imperative. As a first step in this direction we have analysed the LZa succession as logged in traverse B in terms of an embedded Markov Chain model as employed by Doveton (1971) for a Carboniferous sedimentary succession. The principal question which is addressed is whether macrolayers in LZa of the Lille Kufjord Intrusion occur independently of the preceding macrolayer or exhibit first or higher-order

Markovian properties (Davis 1986). The statistical data in combination with field observations are then employed to deduce the nature of any repeated sequences of macrolayers. Adopting the recommendation of Irvine (1982), the latter are referred to as macrorhythmic units.

In order to avoid the problem of choosing an appropriate sampling interval, the LZa succession as developed along traverse B has been reduced to a sequence of 41 changes in lithology. The frequency matrix for the one-step upward transitions between the various macrolayer types is presented in Table 3a. The corresponding transition probabilities, calculated by dividing each element in the transition matrix by the appropriate row total, are given in Table 3b. Note that diagonal elements in both matrices are missing since only transitions are considered and a macrolayer cannot be succeeded by one of the same type.

The significance of the upward-transition frequencies in Table 3a can be tested against a frequency matrix calculated on the assumption that successive layers are independent (Table 3c). The calculation of the expected frequency matrix assuming independence has been carried out using the iterative method described by Davis (1986) and can be compared with the observed frequencies using the chi^2 statistic. The comparison yields a test statistic of 19.60. The critical value for chi^2 for 5 degrees of freedom and an 0.01 level of significance is 15.09, which is exceeded by the test statistic. The conclusion to be drawn is that the successive macrolayers encountered in traverse B are not independent but exhibit a strong first-order Markovian property. This inference implies that the sequence of macrolayers is a result of a combination of deterministic and random processes. The Markovian property is regarded as a decisive argument against the interpretation of layers of oC as intrusive sills.

The possibility that the LZa sequence exhibits additional second-order Markovian properties has been tested by comparison of the observed, two-step, upward-transition frequencies with a Markov-1 prediction using the chi^2 statistic. The comparison yielded a negative result, i.e. the null hypothesis, that second-order Markovian properties are absent, is accepted.

Due to the relatively small number of layer boundaries present in traverse B, rigorous statistical analysis of the significance of individual one-step layer transitions is regarded as unjustified. Table 3b shows, however, that the layer type most likely to succeed a macrolayer of pdoC is oC. Upward transitions from oC to doC and doC to pdoC have slightly lower

A. Observed one-step, upward-transition frequencies.

		TO: A	B	C	D	Row totals
FROM	A	–	11	3	0	14
	B	2	–	10	1	13
	C	11	2	–	0	13
	D	1	0	0	–	1
Col. totals		14	13	13	1	41

B. One-step, upward-transition probabilities.

		TO: A	B	C	D	Row totals
FROM	A	–	0.79	0.21	0	1.00
	B	0.15	–	0.77	0.08	1.00
	C	0.85	0.15	–	0	1.00
	D	1.00	0	0	–	1.00

C. Expected one-step, upward-transition frequencies assuming independence between successive states.

		TO: A	B	C	D	Row totals
FROM	A	–	7	7	(0.4)	14
	B	7	–	6	(0.3)	13
	C	7	6	–	(0.3)	13
	D	(0.4)	(0.3)	(0.3)	–	1
Col. totals		14	13	13	1	41

A = oC; B = doC; C = pdoC; D = poC;

Table 3. Transition matrices for LZa in the Lille Kufjord Intrusion as developed in traverse B.

probabilities than upward transitions from pdoC to oC. Nevertheless, these probabilities are higher than expected in a purely random sequence. Since only a single poC macrolayer was encountered intraverse B and this was followed by oC, the probability of 1.00 for the poC to oC transition is artificially high. Upward transitions from macrolayers of oC to pdoC, from doC to oC and from pdoC to doC occur, but are less frequent than predicted assuming independence of successive lithologies (compare Table 3a and 3c).

Assuming that the most abundant lithology (pdoC) represents the initial state, the sequence of transitions between macrolayers with the highest probability is pdoC/oC/doC/pdoC with a cumulative probability of 0.517. Sequences of this type are common in the logged section but do not necessarily consitute repeated natural units. Neither the upward transition frequencies nor the equivalent probabilities indicate which of the possible sequences may be considered as repeated macrorhythmic units. Fortunately, the field relationships are unequivocal. The bases of layers of oC are invariably sharp while they are commonly bounded upwards by alternations of thin layers of oC and doC forming succeeding macrolayers of doC. The bases of macrolayers of pdoC are also generally more mafic than their upper portions and exhibit alternations of layers of doC and pdoC. These observations strongly suggest that a sequence of macrolayers consisting of oC successively overlain by doC and pdoC is the basic repeated unit in traverse B.

Since the number of cumulus minerals increases systematically through the sequence oC/doC/pdoC, units consisting of these layers can be classified as ideal units (Robins et al. 1987). They are also the most common layer sequence, encountered 8 times in traverse B (Fig. 3), and hence represent the modal unit. Other layer sequences, for instance oC/doC (followed by oC) and doC/pdoC (followed by oC or doC), can be regarded as deviants from the basic type. The oC/doC sequence occurs only twice in traverse B and forms uncompleted units in the classification proposed by Robins et al. (1987). Their presence suggests that the processes which produced ideal units on a particular part of the floor of the magma chamber could occasionally be terminated prematurely. Two units consisting of doC followed by pdoC, have been encountered in traverse B. Evidently, these reduced units (Robins et al. 1987) demonstrate that the formation of a unit could be initiated at some places in the magma chamber at an apparently later stage of differentiation than that represented by the basal oC layers of ideal units. In addition, interrupted units (Robins et al. 1987) consisting of oC followed directly by pdoC are represented 3 times in traverse B. They suggest that the processes forming macrorhythmic units could follow alternative paths.

Macrorhythmic units of the ideal type may be tentatively interpreted as macrocyclic units representing the order of appearance of minerals on the liquidus during progressive fractional crystallization of a particular and repeatedly-intruded magma type. The crystallization order of a magma is dependent on its composition and the physical conditions under which it cools. Batches of compositionally-similar magma introduced successively into the same chamber will therefore exhibit a predetermined crystallization order. This is a reasonable explanation of the Markovian properties of the LZa sequence as developed in traverse B. The validity of this traditional interpretation and the nature of the processes which contributed to the random features of the LZa succession are explored in later sections of this contribution.

Lateral continuity

Mapping of the LZa outcrop has revealed that prominent inter-layer boundaries and groups of macrolayers can be traced for distances of up to 2.7 km, continuity of outcrop being broken only by screes and a series of relatively minor faults (Plate 1). The dominantly melanocratic macrolayers forming the interval between 55 and 105 m in the sequence logged in traverse B form, for instance, a bold topographic feature or a series of marked bluffs along the whole of the outcrop of LZa. Similarly, the thick layers of oC and doC occurring at the bases of macrorhythmic units 9 and 10 as defined in traverse B can be traced over almost the whole area. Logging of parts of the LZa succession along several, spaced traverses has, however, revealed significant lateral variations in the number, thickness and nature of macrorhythmic units.

Variation in the number of identifiable macrorhythmic units is illustrated by comparison of equivalent parts of the LZa sequence as developed in traverses A, B, C and D (Fig. 7). In traverse B the stratigraphic interval between

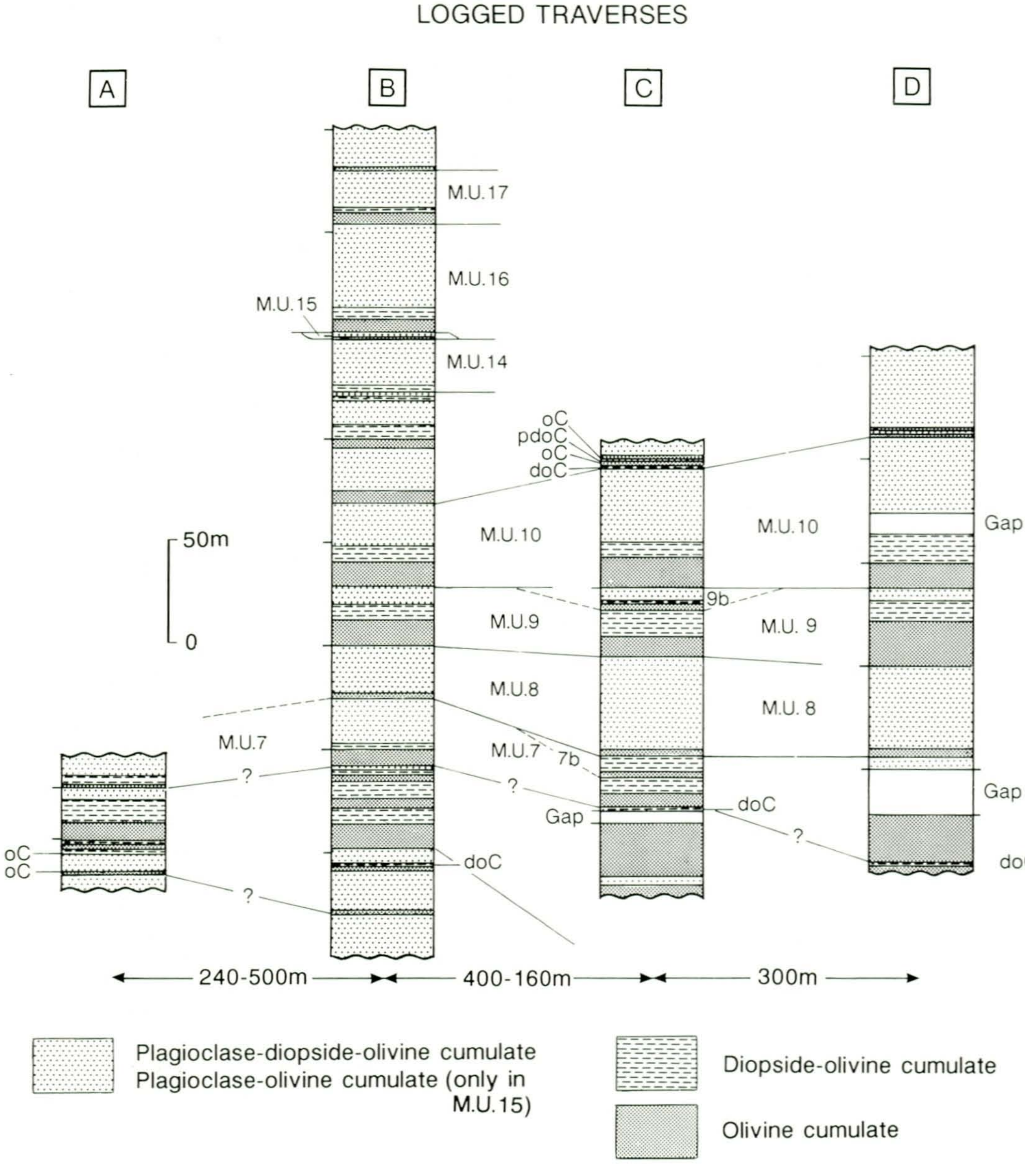

Fig. 7. Layer sequences logged along traverses A-D (Plate 1) showing correlated layer boundaries. Note the southward thickening of macrorhythmic units 7-9 from traverse B to traverseC and the condensed sequence in traverse A relative to the equivalent part of traverse B. MU 7b and 9b encountered in traverse C, as well as MU 15 in traverse B, appear to be laterally impersistent units.

150 and 217 m can be subdivided into two ideal macrorhythmic units (MU 9 and 10). They are distinctive in that the oC- doC layers they contain are sandwiched between thick sequences of gabbroic cumulates. The same units are encountered in traverse D, though their total thickness is larger (111 m versus 66 m) and the relative thicknesses of their constituent macrolayers is somewhat different. In the intervening traverse (traverse C), however,

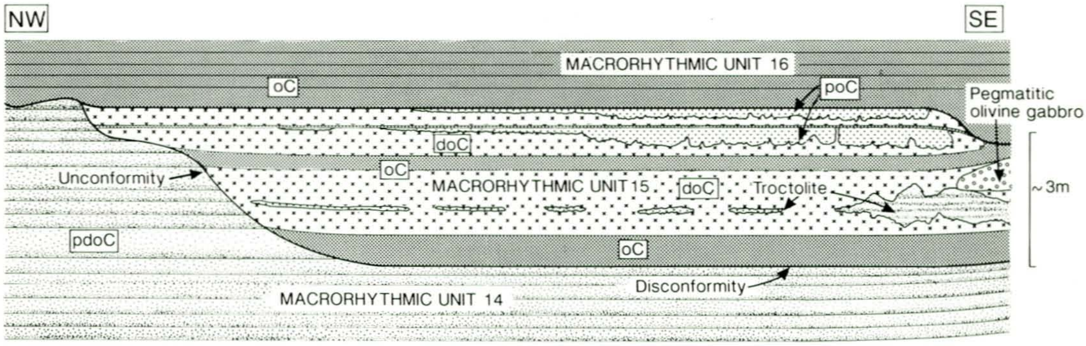

Fig. 8. Sketch, constructed largely from field and aerial photographs, illustrating the stratigraphic relations between Macrorhythmic Units 14, 15 and 16 as revealed on the cliffs adjacent to traverse B (Plate 1). MU 15 resides in a shallow depression eroded in the cumulates forming the upper part of MU 14 and is bounded upwards by a phase boundary which is locally discordant. Note the highly-irregular and, in the upper part of unit 15, fingered contacts between layers of poC and doC and the lateral impersistence of troctolitic layers. Horizontal scale = vertical scale.

MU 9 is separated from MU 10 by a 10 m-thick unit of the ideal type(MU 9b in Fig. 7). Furthermore, MU 9 here consists only of a oC-doC sequence. Due to discontinuous exposures and the intervention of a fault, it has not been possible to deduce the two-dimensional geometry and contact relationships of the macrolayers forming MU 9b.

The relatively thin macrolayers grouped together as MU 15 in traverse B also have a restricted lateral extent. They are exposed at the end of a cliff and only accessible for a distance of about 30 m from the adjacent scree (see Robins 1982, Fig. 3). Inspection of enlargements of aerial photographs has revealed, however, that MU 15 resides in a shallow depression cut into the modally-layered olivine gabbros of the underlying unit (Fig. 8). It follows that MU 15 rests on a disconformable to unconformable lower boundary. The basal olivine cumulate macrolayer of MU 16 can be traced laterally from where it rests on rocks forming the uppermost part of MU 14 onto those at the summit of MU 15. The lower contact of MU 16 thus also appears to be disconformable. Within a few metres of the scree it cuts downwards through the uppermost layers of MU 15 (see Robins 1982, Fig. 4.). These particularly clear, cross-cutting relationships may be exceptional but suffice to show that some macrolayers were eroded to varying degrees after their formation (and even eliminated) and also suggest that other laterally impersistent macrorhythmic units, such as MU 9b, may also occupy erosional depressions. Indeed MU 9 as developed along traverse C may not be an uncompleted unit (implying that its development never reached the stage represented elsewhere by a pdoC macrolayer), but may instead have been beheaded by mechanical or thermo-chemical erosion.

The logged traverses suggest that at least the lower part of the LZa sequence thickens southwards (Fig. 7). The group of dominantly melanocratic macrolayers encountered in traverse A has a total thickness of 38 m. In traverse B the equivalent group has increased in thickness to 50 m. Logging along traverse C began within the group but nevertheless the thickness of macrolayers belonging to it was measured to 61 m. There are similar increases in the thicknesses of the melanocratic macrolayers within MU's 9 and 10. Certain macrolayers and macrorhythmic units, however, thin southwards. The pattern of slightly wedge-shaped layers and macrorhythmic units suggests varying local conditions superimposed on a general tendency for thicker developments of cumulates towards the south.

Mapping and logging of LZa has revealed no systematic changes in the internal composition of macrorhythmic units of the type demonstrated in the Honningsvåg Intrusive Suite (Robins et al. 1987). When individual units are traced along strike they generally retain their characteristic layer sequences. It may be significant in this respect that the exposed section through LZa is almost parallel to the axial trace of the syncline defined by the layering in the intrusion. Experience in the Honningsvåg

Intrusive Suite and other intrusions leads us to suspect that variations in the composition of macrorhythmic units are most pronounced in directions away from the axes of magma chambers. The northwards thinning of the LZa sequence in the Lille Kufjord Intrusion may, however, be related to increasing distance from the inferred position of the feeder, beneath Store Kufjord.

Thicknesses of macrorhythmic units and macrolayers

If the sequences of macrolayers in macrorhythmic units are principally the result of the fractional crystallization of batches of magma introduced into the Lille Kufjord magma chamber, as suggested above, then stratigraphic sequences in LZa should carry information bearing on several important petrological questions. The absolute thicknesses of oC macrolayers should be a function of the composition and volume of the batches of magma; the thicknesses of pdoC macrolayers will be a function of the repose times separating episodes of magma inflow. The sequence and relative thicknesses of macrolayers in units should reflect the fractionation paths followed by the magmas through compositional space. Differences in the paths may throw light on the importance of compositional variations in the introduced magmas (due, for instance, to effects in their source region or variable amounts of previous fractional crystallization), mixing of batches of new magma with the magma already residing in the chamber or assimilation of chamber walls and older cumulates. The stratigraphic record of magma-chamber events can, however, be expected to be incomplete, due, for instance, to local non-deposition or the partial to complete removal of macrolayers by erosion. Unconformities and disconformities are particularly likely to have been associated with the inflow of magma and do, in fact, appear to form the bases of some macrorhythmic units, as described above.

The macrorhythmic units recognized in traverse B vary considerably in thickness. The thinnest unit of the ideal type (MU 6, Fig. 3) is only 6 m thick. MU 16, also an ideal unit, has a thickness of 53 m and represents the other extreme. The thinnest unit of any kind in traverse B is unit 13 which consists of a doC-pdoC combination just 4.9 m thick. Of more interest than the dimensions of units themselves is the

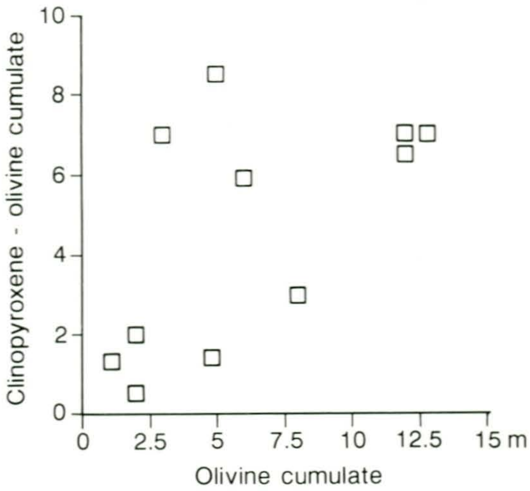

Fig. 9. Plot of the thicknesses of macrolayers of oC and succeeding layers of doC as measured in traverse B.

relative thicknesses of their constituent macrolayers. Even a cursory examination of Fig. 3 is sufficient to demonstrate the lack of any correlation between thicknesses of pdoC macrolayers and their attendant, underlying layers. As noted earlier, macrolayers of oC are not always succeeded by doC, and in certain macrorhythmic units doC forms the basal macrolayer. There is, however, a crude correlation between the thicknesses of oC and immediately overlying doC macrolayers (Fig. 9). In addition, Fig. 9 shows that in slightly more than half of the oC-doC sequences encountered in traverse B, the doC macrolayer is thinner than the preceeding oC macrolayer. The implication of these relationships is that magmas introduced into the Lille Kufjord chamber commonly followed similar paths through compositional space, but significant variations in the paths were possible. A full discussion of the relative importance of various parameters including compositional variations in the introduced magmas, magma mixing, assimilation and the shape of the floor of the magma chamber is, however, deferred to a later section.

The stratigraphic variation in thicknesses of macrolayers of oC observed in traverse B is presented in Fig. 3. The latter appears to show a rhythmic pattern in that a thick macrolayer of oC tends to be followed up-sequence by layers of oC with diminishing thickness. If this cyclic pattern is significant it may point to the operation of rhythmic processes in the source region of the magmas or within the conduit between the source and the Lille Kufjord magma chamber.

Small-scale modal layering

Sequences of modally-distinctive layers characterize macrolayers of doC and pdoC. They are tabular and can be up to 1 m thick but generally are between 10 and 30 cm in thickness. Boundaries between layers are sharp to diffuse and planar, wavy or fingered.

In most pdoC macrolayers, modally-graded layers varying upwards from olivine melagabbro to olivine leucogabbro alternate with isomodal layers of olivine gabbro. Elsewhere, and particularly within the more melanocratic basal portions of macrolayers of pdoC, modal layers occur in dark-light pairs separated by rapid transitions or sharp boundaries (Fig. 10). The darker members of these pairs are generally diopside-olivine cumulates and the upper members melanocratic diopside-olivine-plagioclase cumulates. In the latter, the modal proportion of plagioclase generally increases upwards, as does the concentration of plagioclase-rich xenoliths. More rarely, layers consist of olivine cumulate overlain successively by doC and pdoC. Macrolayers of doC generally also consist of small-scale layers consisting of oC overlain by layers of doC. While upper and lower boundaries of these layer combinations are generally planar, the contacts between their members may be planar and concordant with the fabric in the cumulates, as defined by orientated laths of plagioclase or feldspathic xenoliths, or discordant and wavy (Fig. 11).

The most markedly discordant contacts are those separating doC (below) and poC (above) in two sequences of layers forming the upper part of MU 15 as defined in traverse B. The basal oC members in the sequences are separated from the succeeding doC layers by sharp, planar contacts (Fig. 8). In contrast, the upper contacts of the doC layers form a series of rounded bulges and pinnacles which trangress the planar modal and mineral lamination in the overlying poC as well as the xenoliths it contains. In places the contacts cut completely through the poC layers. These particular contacts have been described by Robins (1982) who called them finger structures and compared them with similar contacts separating olivine cumulates from plagioclase-olivine cumulates in the Rhum Intrusion.

Fig. 10. Small-scale modal layering characteristic of the lower, melanocratic portions of macrolayers of pdoC. The lower parts of individual layers consist of diopside-olivine cumulate which grades rapidly upwards into plagioclase-diopside-olivine cumulate. The orientated, light-coloured lenticlar objects which are present in both types of cumulate are plagioclase-rich xenoliths (see Fig. 6).

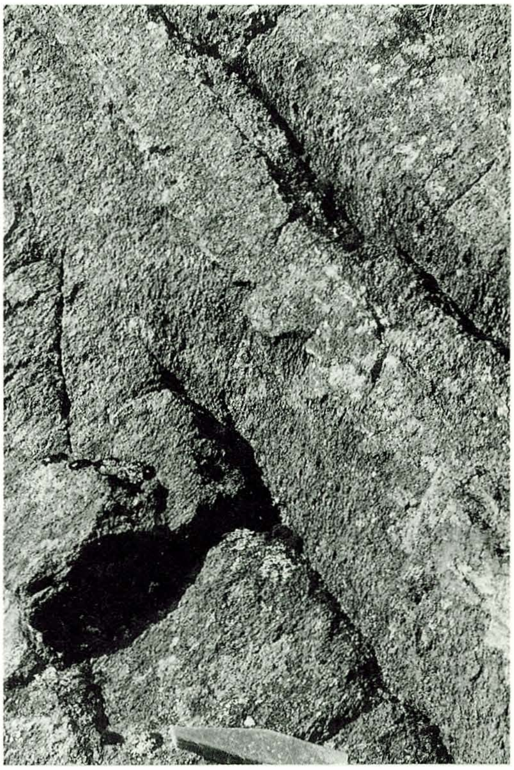

Fig. 11. Alternating, sharply-bounded layers of doC (exhibiting the rougher weathered surfaces) and olivine melagabbro in the basal part of the pdoC macrolayer in macrorhythmic unit 9b encountered in traverse C (Fig. 7). The base of the uppermost layer of olivine melagabbro is planar while that in the centre of the photograph is in places highly irregular (fingered) and discordant to the internal fabric in the melagabbro.

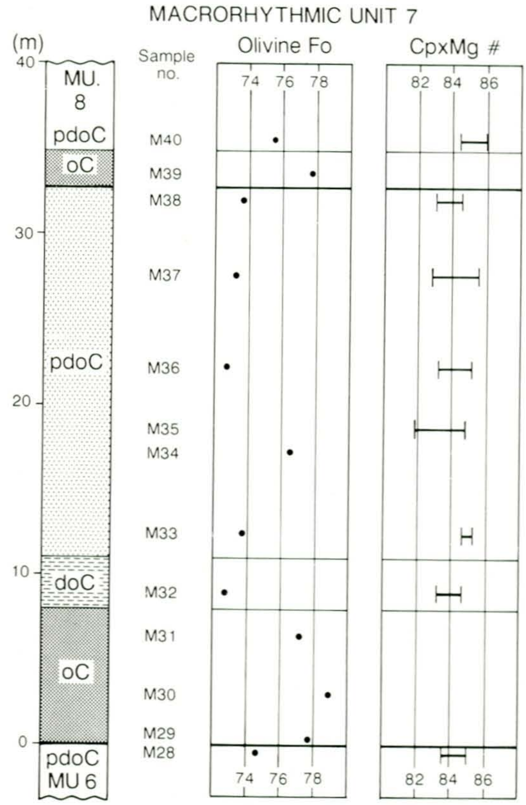

Fig. 12. Generalized layer sequence and variation in the composition of cumulus olivine and Ca-rich pyroxene in macrorhythmic unit 7 as sampled in traverse B. Heights (in metres are referred to the base of the unit.

Cryptic layering in selected macrorhythmic units

Two prominent macrorhythmic units encountered in traverse B have been sampled for investigation of the degree and nature of any systematic stratigraphic variations in mineral chemistry. These units, MU 7 and MU 10 (Fig. 3), are both of the ideal type but the relative proportions of their constituent cumulates are different. MU 10 encompasses a 38 m-thick sequence, including a 12 m-thick oC macrolayer (31.6%), a 6.5 m-thick, modally-layered doC macrolayer (17.1%) and a 19.5 m-thick, modally-layered macrolayer of pdoC (51.3%). Fourteen samples were collected through the unit, with an average spacing of 2.5 m. Three additional samples, 2 from the underlying pdoC and 1 from the succeeding oC, have also been investigated. MU 7 has a measured thickness of 32.7 m and consists of 8.0 m of oC (24.5%), 3 m of doC (9.2%) and 21.7 m of pdoC (66.4%). Ten samples collected from this unit at intervals of 2-5 m and a further 3 samples collected immediately above and below the unit boundaries were investigated.

The composition of cumulus minerals was determined using an ARL electron microprobe and standard wavelength-dispersive techniques (Reed 1975). Analyses were carried out using an accelerating voltage of 15 kV, beam currents of 10-20 nA and ZAF data reduction (Colby 1968). Synthetic oxides, pure metals and well-characterized or simple, stoichometric minerals were employed as standards. Typically, 3 point analyses were carried out in 3 crystals of each cumulus mineral. Analytical results are plotted in Figs. 12 and 13 and representative analyses are reported in Tables 4, 5 and 6.

Whole-rock sulphur concentrations in the samples from MU 10 (Fig. 13) were determined by XRF. Analytical data were corrected for matrix effects using the alpha method (de Jongh 1971).

Sample no.	M-30	M-32	M-37	MG-17	MG-33	MG-41
Rock type	oC	doC	pdoC	oC	doC	pdoC
Unit	7	7	7	10	10	10
Strat. ht.*	3	9	27.5	1	13	37
SiO_2	38.41	37.66	36.84	38.53	38.17	37.56
FeO	19.74	24.91	24.62	19.01	21.48	23.96
MnO	0.28	0.33	0.25	0.24	0.27	0.28
NiO	0.14	0.10	0.16	0.16	0.13	0.15
MgO	41.32	37.22	37.66	42.27	39.82	38.22
CaO	0.03	0.00	0.01	0.01	0.01	0.00
Total	99.92	100.23	99.54	100.23	99.88	100.17

No. of cations on the basis of four O						
Si	0.989	0.991	0.977	0.986	0.991	0.985
Fe^{2+}	0.425	0.548	0.546	0.407	0.467	0.526
Mn	0.006	0.007	0.005	0.005	0.006	0.006
Ni	0.003	0.002	0.004	0.003	0.003	0.003
Mg	1.587	1.460	1.489	1.612	1.542	1.494
Ca	0.001	0.000	0.000	0.000	0.000	0.000
Total	2.02	2.02	2.04	2.03	2.02	2.03
mg#	78.9	72.7	73.2	79.6	76.5	73.8

* Height (in metres) above base of unit as developed in traverse B.

Table 4.
Representative electron microprobe analyses of olivine from macrorhythmic units 7 and 10.

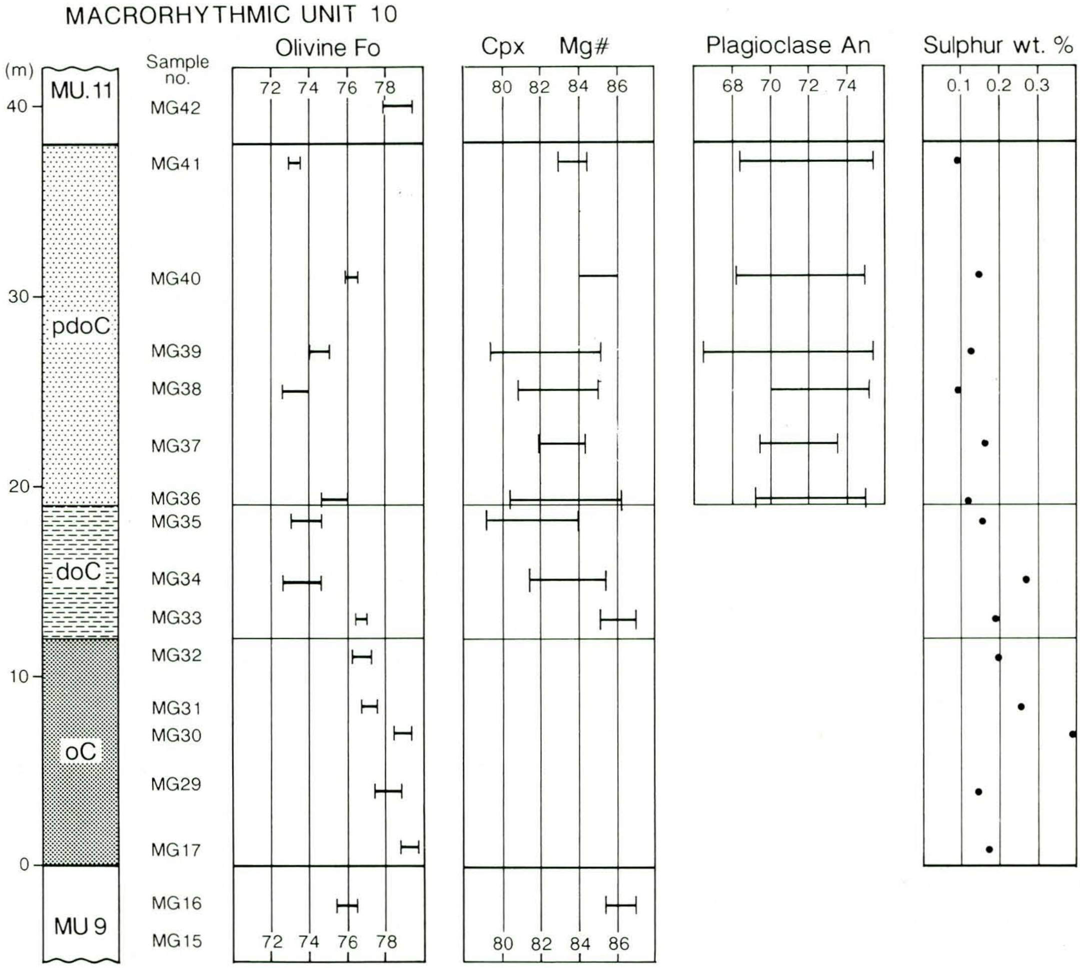

Fig. 13. Generalized layer sequence and variation in the composition of cumulus olivine, Ca-rich pyroxene and plagioclase in macrorhythmic unit 10 as sampled in traverse B. The whole-rock sulphur concentrations are based on XRF data. Heights (in metres) are referred to the base of the unit.

Olivine

Olivine in the samples from MUs 7 and 10 exhibits almost identical ranges in composition: Fo 72.5-79.7 in MU 10 and Fo 72.7-78.9 in MU 7. Within individual samples the variation in olivine composition is so limited (generally <2 mol.% Fo) that the between-sample variation must be regarded as significant.

The most magnesian olivine in MU 10 is found in the lower half of the oC macrolayer. Olivine in the lowest sample from the unit has a significantly higher mg# (=100Mg/Mg+Fe) than the olivine near the summit of the underlying macrorhythmic unit, tending to support the interpretation of the lower boundary of the oC as a regressive discontinuity (Irvine 1982). Olivine appears to become systematically less magnesian upwards through the oC macrolayer. This trend does not, however, persist into the upper part of the unit. Olivine in the doC and pdoC macrolayers exhibits irregular variations in composition. Although olivine in the upper part of the unit is generally more iron-rich than the in the oC, one sample of pdoC (MG40) contains olivine as magnesian as those in the underlying oC.

In MU 7 the variation in olivine composition exhibits much the same pattern as in MU 10. The most magnesian olivine is found in the oC macrolayer. In the remainder of the unit olivine maintains a fairly constant composition. One sample (M-34) from near the middle of the pdoC macrolayer in MU 7 (Fig. 12) contains an anomalously magnesian olivine. This sample was collected from a prominent layer of olivine cumulate forming the basal part of an oC-doC-pdoC sequence. The association in sample M-34 of magnesian olivine with a high modal proportion of olivine suggests that re-equilibration during crystallization of intercumulus melt may have exerted a less important influence on the final composition of olivine in this cumulate than in the other analysed samples. This process, termed the trapped-liquid shift by Barnes (1986), may result in post-accumulation changes in the composition of fractionated olivine due to Mg-Fe exchange with differentiating melt. The importance of the changes depends on the relative amounts of interstitial melt and crystals and the degree of intracrystalline ionic mobility. In view of the lack of compositional zoning in the analysed olivines, suggesting extensive re-equilibration during cooling, it would appear possible that the occurrence of the most magnesian olivine in the olivine-cumulate macrolayers simply reflects the high abundance of cumulus olivine in these layers. The limited total compositional variation exhibited by olivine in MUs 7 & 10 could to some degree also be the result of the varying abundance of cumulus olivine.

Ca-rich pyroxene

Clinopyroxenes in samples from the upper two macrolayers of MU 10 & MU 7 are diopside or augite with mg# (=100Mg/Mg+Fe) varying from 79.2 to 87.1. The range in mg# exhibited by pyroxene crystals within individual samples is relatively large (up to 6 atomic % Mg) and overshadows any regular stratigraphic variation in composition that may have been present in pyroxene primocrysts. The maximium mg# for Ca-rich pyroxene in the three samples from the doC macrolayer in MU 10 appears, however, to show an upward decrease. In the pdoC macrolayers, maximum mg# as determined in the samples analysed varies little and unsystematically. Pyroxene in the pdoC also show the same range in mg# as pyroxene in the doC macrolayers.

Plagioclase

Plagioclase in samples from the pdoC macrolayer in MU 10 varies in composition from An 75.7 to An 65.0 (Fig. 13). In all samples plagioclase exhibits compositionally-zoned margins, but the calcic cores of grains provide no evidence for time-related variations in composition which could be related to fractional crystallization in the Lille Kufjord magma chamber. The compositional zoning does, however, demonstrate the ortho- or mesocumulate status of the cumulates and the limited degree to which cumulus plagioclase re-equilibrated during the crystallization of trapped magma and later subsolidus cooling.

Sulphides

Rounded, composite sulphide grains occur in accessory amounts throughout MU 7 & 10 and probably represent crystallization of monosulphide solid solution from an immiscible sulphide liquid. The drop-like grains now consist predominantly of pyrrhotite together with small amounts of chalcopyrite and pentlandite. The amount of sulphides in MU 10, as indicated by the bulk-rock concentration of sulphur, is highest in the upper part of the oC macrolayer and the lower part of the doC macrolayer (Fig. 13). Above this region, sulphur concentrations exhibit an irregular decrease to low values in the pdoC macrolayer.

Interpretation of the macrorhythmic units

The observations presented above are in essence stratigraphic and must be interpreted in terms of dynamic processes taking place during the evolution of the Lille Kufjord magma chamber. Repetitions of a single layer sequence (oC-doC-pdoC) builds up most of LZa and indicates the repeated operation of a singular cyclic process during this interval in the life of the magma chamber. The variations on the most common layer sequence which constitute a smaller number of macrorhythmic units in LZa nevertheless suggest the recurrence of a number of other phenomena during crystallization. In the following sections the stratigraphic observations from the Layered Series in general and LZa in particular are integrated into a complex evolutionary model for the Lille Kufjord magma chamber. Implications of the model for the genesis and later modification

Sample no.	M-32	M-33	M-38	MG-33	MG-36	MG-41
Rock type	doC	pdoC	pdoC	doC	pdoC	pdoC
Unit	7	7	7	10	10	101
Strat. ht.*	9	12.4	32	13	19.3	37
SiO_2	52.28	53.18	49.96	52.12	51.59	51.63
TiO_2	0.77	0.93	0.75	0.76	0.62	0.70
Al_2O_3	4.54	5.49	5.37	4.35	4.52	5.15
Cr_2O_3	0.41	0.43	0.41	0.48	0.34	0.38
FeO	5.14	4.62	4.64	4.21	4.92	4.81
MnO	0.16	0.11	0.21	0.16	0.11	0.12
MgO	15.25	15.12	14.84	15.00	14.72	13.92
CaO	19.92	19.23	21.94	22.14	21.64	22.18
Na_2	0.78	0.88	0.87	0.89	0.81	0.91
Total	99.25	99.99	98.99	100.12	99.27	99.81
No. of cations on the basis of six O						
Si	1.910	1.923	1.856	1.904	1.904	1.896
Al^{iv}	0.090	0.077	0.145	0.096	0.096	0.104
Al^{vi}	0.106	0.157	0.090	0.092	0.101	0.119
Ti	0.023	0.025	0.021	0.021	0.017	0.019
Cr	0.013	0.012	0.012	0.014	0.010	0.011
Fe^{2+}	0.157	0.140	0.144	0.129	0.152	0.148
Mn	0.005	0.003	0.007	0.005	0.004	0.004
Mg	0.828	0.815	0.822	0.817	0.810	0.762
Ca	0.783	0.745	0.873	0.867	0.855	0.873
Na	0.056	0.062	0.063	0.063	0.058	0.065
Total	1.971	1.959	2.032	2.008	2.007	2.001
mg#	83.6	85.1	84.5	85.9	83.8	83.4

* Height (in metres) above base of unit as developed in traverse B.

Table 5.
Representative compositions (averages of 9 point electron microprobe analyses) of cumulus Ca-rich pyroxene from macrorhythmic units 7 and 10.

Sample no.	MG-36	MG-40	MG-41
Rock type	pdoC	pdoC	pdoC
Strat. ht.*	19.3	31	37
SiO_2	50.79	50.79	51.79
Al_2O_3	31.57	30.71	31.95
CaO	14.13	14.03	14.84
Na_2O	2.94	3.08	3.05
K_2O	0.06	0.09	0.11
Total	99.49	98.70	101.74
No. of cations on the basis of eight O			
Si	2.316	2.336	2.315
Al	1.697	1.665	1.683
Total Z	4.013	4.001	3.998
Ca	0.690	0.692	0.711
Na	0.260	0.275	0.264
K	0.004	0.005	0.007
Total X	0.954	0.972	0.982
An%	72.6	71.6	72.9

* Height (in metres) above base of unit as developed in traverse B.

Table 6.
Representative averages of electron microprobe analyses of cumulus plagioclase from macrorhythmic unit 10.

of the Lille Kufjord Marginal Series and the significance of some of the deductions for the interpretation of layered intrusions in general are discussed.

Parental magmas and fractionation paths

The modal composition, mineral chemistry and textural relationships of LZ cumulates in the Lille Kufjord Intrusion are all consistent with a subalkaline olivine basalt parental magma. There is textural evidence in the cumulates for a peritectic at which cumulus olivine reacted with differentiated pore melts to produce orthopyroxene and this is mirrored in the stratigraphy of the Layered Series by the entry of cumulus orthopyroxene and disappearance of cumulus olivine at the Lower Zone/Upper Zone boundary. Intercumulus hornblende appears in virtually all of the LZ cumulates and is abundant in some varieties. Its presence indicates that the water content of parental magmas was sufficient to stabilize hornblende after moderate degrees of intercumulus crystallization. The composition of the most magnesian olivine (Fo82, in oC) suggests that the magmas introduced into the Lille Kufjord magma chamber were not primary but had undergone previous fractional crystallization (and contamination?) during ascent from their source region. Noble-metal patterns of olivine and diopside-olivine cumulates from macrorhythmic unit 10 resemble those of high-MgO (12-18%) basalts, but high Ni/Pd and Cu/Ir ratios indicate sulphide segregation and scavenging of noble metals from the magma prior to emplacement (Barnes et al. 1988).

The most common layer sequences observed (oC-doC-pdoC, see above) suggest that magmas which repeatedly invaded the Lille Kufjord chamber during the crystallization of LZa had olivine as their first liquidus phase. These magmas subsequently evolved through compositional space onto and along an olivine-augite cotectic as they cooled and crystallized. However, the magma which cooled in the chamber during most of the time represented by the accumulation of LZa crystallized along a three-phase (plagioclase-augite-olivine) cotectic (Fig. 15A). Magma crystallising exclusively along this cotectic was present in the magma chamber during the formation of LZb. During this interval of time the magma chamber appears to have evolved as a closed system and differentiation eventually resulted in the cessation of olivine crystallization and the stabilization of orthopyroxene on the liquidus, marked in the cumulate stratigraphy by the LZ/UZ boundary. The composition of olivine just prior to its cumulus termination was about Fo70, more magnesian than in the Skaergaard Intrusion where the olivine gap is Fo52-36 (Wager & Brown 1968). This difference between the two intrusions suggests a higher silica activity in the Lille Kufjord magma. During the formation of the UZ cumulates the magma chamber appears to have continued to cool without frequent or major perturbation due to the inflow of magma. The recurrence of rare olivine gabbro layers within the gabbronorite UZ cumulates does suggest, however, the occasional addition of magma which caused crystallization to revert to an earlier stage in the general differentiation trend.

As noted above, macrolayers of oC may be succeeded by pdoC without the intervention of a doC macrolayer. Although infrequent, only three sequences of this type having been identified in LZa along traverse B, they may indicate that magmas emplaced into the chamber during the LZa time interval had variable compositions and exhibited different crystallization sequences. A simple ad hoc explanation of interrupted macrorhythmic units, that the magmas introduced into the chamber occasionally had compositions such that their order of crystallization was olivine followed by the simultaneous appearance of plagioclase and clinopyroxene, is rejected on the grounds that it appeals to coincidence and leaves the relationship between these and the more voluminous magmas unexplained. Gradual blending of new magma with more-differentiated, resident magma or assimilation of differentiated rocks in new magma are alternative hypotheses. These mixing phenomena can be envisaged as having forced liquid compositions along curved paths through the olivine phase volume to coincidental intersections with the plagioclase-clinopyroxene-olivine cotectic. The preferred explanation of interrupted units, formulated below, appeals to withdrawal of magma from a stratified chamber.

The rare macrorhythmic units consisting of doC followed by pdoC present a rather different problem of interpretation. They may have resulted from emplacement of batches of magma which were more differentiated than those which precipitated olivine cumulates, due for instance to previous fractional crystallization within the feeder system. An alternative hypothesis is that formulated for reduced units in the Honningsvåg Intrusive Suite (Robins et al. 1987) i.e. simultaneous crystallization of doC and oC from a compositionally-zoned magma column at different places on an inclined (or irregular) magma-chamber floor following emplacement of magma with olivine as the sole liquidus phase. As noted above there is stratigraphic evidence for disconformities and local unconformities in LZa suggesting the local removal of parts of the cumulate sequence, probably during episodes when magma was flowing into the chamber. It would seem reasonable to conclude that local depressions and elevations indeed existed in the floor of the chamber at different times in its evolution and that these, together with the more regular slopes indicated by variations in the thickness of particular sections of the LZa stratigraphy, may have controlled the localisation of cumulates crystallizing from a zoned magma.

The oldest exposed cumulates, at the base of LZa, contain the most iron-rich olivine (Fo71-66) found so far in the Layered Series (Fig. 3). In the lowest 150 m of the LZa sequence olivine exhibits an irregular, upward trend to more magnesian compositions as measured in equivalent cumulate types (Fig. 3). This pattern suggests that the initial formation of LZa resulted from fractional crystallization of relatively differentiated magmas. The magma introduced into the chamber during the deposition of the lower part of LZa appears, however, to have been sufficiently voluminous to more than offset fractional crystallization. Thus, the resident magma gradually became less differentiated until a quasi steady state was attained in the magma chamber, the rate of magma inflow approximately balancing the effects of fractional crystallization.

The significance of the Marginal Series

In the preceding description of the Lille Kufjord Marginal Series attention was drawn to similarities with the Skaergaard Marginal Border Series. The striking structural parallels which exist between these units do not, however, extend to their relationships with the adjacent Layered Series. In the Skaergaard Intrusion the cryptic layering of the Layered Series is in most respects reproduced in the Marginal Border Series (Hoover 1978, 1989). This is not the case with the Lille Kufjord Intrusion. The modal composition and mineralogy of the Lille Kufjord Marginal Series where in contact with LZb olivine gabbros have little affinity with either LZb or LZa cumulates. The pyroxenes of typical, non-pegmatitic, Marginal Series gabbronorites exhibit compositions more akin to those within UZ cumulates. Analysis of the rare olivine that occurs locally in the Marginal Series reveals that it is more fayalitic than any analysed olivine from the Layered Series (Table 2). Plagioclase in the Marginal Series varies considerably in composition (An 83-59), but in certain samples is more calcic than the feldspar which characterises the Layered Series. The conclusion that the LZa cumulates and the Marginal Series crystallized from compositionally different magmas seems inescapable. The mineral chemistry of the Marginal Series is consistent with crystallization from a more differentiated magma than that which formed the LZa cumulates and the relatively calcic plagioclases present in some samples suggest that assimilation of aluminous rocks derived from the envelope was locally important in its evolution. Crystallization of the Marginal Series from contaminated magma is supported by the occurrence of gabbronorite pegmatite associated with coarse-grained granitoid and xenoliths of paragneiss.

The Marginal Series is envisaged as having crystallized from cool magma descending along the walls of the magma chamber. The magma carried with it buoyant xenoliths of wall rocks which were being assimilated along their margins as well as undergoing wholesale melting as they were being dragged downwards. Differential movement of xenoliths and the surrounding magma resulted in streaks of contaminated magma from which the asymmetrical gabbronorite pegmatite layers observed in the Marginal Series crystallized. As the magma descended, crystallization took place in the thermal boundary layer against the temporary wall. The presence of crystals increased the density contrast between the boundary layer and the main body of magma occupying the chamber, but at the same time increased its viscosity. The increased viscosity would ultimately have led to a permanently near-stagnant outer zone in the boundary layer (Fig. 16d) in which the interior margin of the Marginal Series could crystallize. Stronger currents plunging down the walls of the chamber on occasion swept away the stagant layer and some of the fragile crystal framework forming the inner part of the Marginal Series, producing near-vertical channels. The latter were coated by later encrustations, producing trough and colloform layering.

Compositional effects due to fractional crystallization of magma along steep cooling surfaces have been invoked by some workers (McBirney et al. 1985, Turner & Campbell 1986) as the most important source of buoyancy involved in driving convection. This hypothesis is not adhered to by the present authors who believe that convection involved in the crystallization of the Marginal Series of the Lille Kufjord Intrusion was predominantly thermal (Fig. 16d). The much smaller thicknesses (and volumes) of marginal series relative to layered series in intrusions in general and the Lille Kufjord Intrusion in particular demonstrates in a graphic manner the inefficiency of crystal-liquid separation along steep boundaries in magma chambers. Nevertheless, crystallization along the inner margin of the Marginal Series may have resulted in a very narrow zone of upward flow of lower-density, differentiated magma (Fig. 16d).

Towards a complex magma-chamber model

The cumulate sequence forming LZa is postulated as having crystallized in a compositionally-zoned magma chamber. The zonation was a consequence of the periodic emplacement of hot, dense magma which underflowed the more-voluminous and more-differentiated magma already residing in the chamber. As the new magma fountained into the chamber it spread into either a discrete basal layer or formed a series of independantly-convecting layers of varying composition, temperature and density (Fig. 16a-c). The subsequent evolution of the magma above the floor of the chamber is envisaged as a complex interplay of thermal convection, fractional crystallization, two-phase convection and compositional convection, all consequences of cooling into the overlying magma (Fig. 16e). As cooling progressed, the configuration of the convection changed by slow migration and abrupt disappearance of double-diffusive interfaces. Cumulates were, however, generated exclusively from the lowermost and hottest convecting layer.

The formation of macrorhythmic units of the most common (modal or ideal) type is proposed to have taken place by the following sequence of processes. Initially, the lowermost magma layer was cooling rapidly along its diffusive interface with overlying cooler magma, leading to the formation of a thin boundary region in which olivine crystals nucleated and grew (Fig. 16f). Instability in this denser region resulted in two-phase convection (Morse 1986, Marsh 1988). Plumes of magma containing suspended olivine continually sank to the floor of the chamber where their velocity was checked and, as the crystal suspensions spread out, crystals settled onto the depositional interface. The less-dense, residual magma was returned and mixed into the main body of the layer. At this early stage, the large difference in temperature across the sharp upper interface of the basal magma layer led to a relatively high degree of undercooling beneath the upper diffusive interface. This resulted in rapid crystal growth relative to the rate of crystal nucleation and the olivines deposited were relatively large. As the basal magma layer approached thermal equilibrium with the overlying magma the degree of undercooling diminished and smaller olivines were transported in and deposited from the descending plumes. Differentiation of the basal layer continued until the magma attained a composition close to the olivine-clinopyroxene cotectic. At this stage some plumes transported only olivine to the floor while others which contained magma which had experienced more cooling in the upper boundary region carried both olivine and clinopyroxene. The latter experienced sorting according to their size and density in the boundary region, during transport in plumes and during deposition on the floor. The origin of the modal layering in doC macrolayers in LZa is thus envisaged as a consequence of the mode of cooling and the nature of the convection which took place in the basal layer. Eventually the magma layer evolved towards a composition close to the plagioclase-clinopyroxene-olivine cotectic as its temperature (and density) decreased. Plagioclase began to crystallize in the upper, coolest part of the thermal boundary region while exclusively olivine and pyroxene were crystallizing in its lower, hotter part. Plumes forming at this stage carried a mixture of the three phases in non-cotectic proportions, the heads of the plumes concentrating olivine and pyroxene while the tails contained all three phases suspended in slightly more-differentiated liquid. Further sorting could take place during the downward and lateral movement of plumes and possibly while crystals sank from suspension onto the floor of the chamber. This phase in the evolution of the basal layer is suggested by the modally-layered olivine melagabbroic cumulates which generally form the basal parts of pdoC macrolayers. Finally the basal magma layer attained a composition on the three-phase cotectic. Crystallization along the diffusive boundary continued to generate crystal-bearing plumes in which mineral phases were crudely sorted according to their sizes and densities. On average, however, the minerals were now deposited in cotectic proportions.

Some workers that have developed magma-chamber models involving stratified liquids have postulated that double-diffusive layering precludes large-scale thermal convection and that primocrysts must have grown in situ on the floor of the magma chamber (e.g. Wilson & Larsen 1985). During double-diffusive convection of the type outlined above the heat flux is, however, upwards. Heat is withdrawn from the lowest convecting layer predominantly through the diffusive interface into the overlying, cooler liquid. Only exceptionally is the floor of the magma chamber a cooling surface. This may be the case early in the life of a basal liquid layer, if it resides on more evolved, cooler cumulates but the formation of high-temperature cumulates from the layer itself soon insulates it from the floor. Since cooling of liquid layers occurs mainly in their upper diffusive boundary layers it must be here that primocrysts arise. They are postulated to have been transported through their parental liquid layer by two-phase convection (Grout 1918), essentially as envisaged by Hess (1960) and Wager & Brown (1968), where they were deposited during the flow of the density current over the floor of the chamber (Irvine 1987). We see no contradiction between doub-

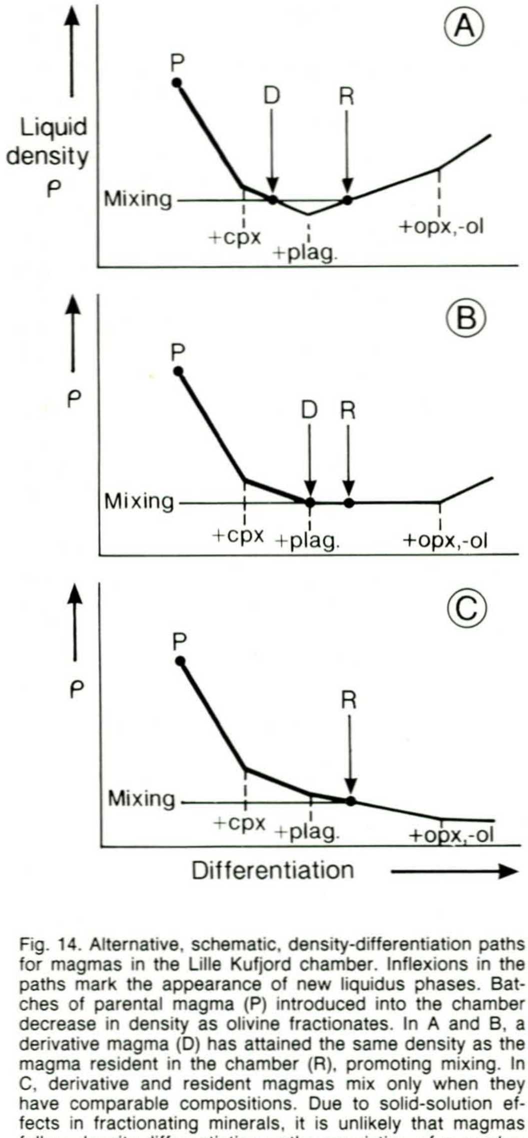

Fig. 14. Alternative, schematic, density-differentiation paths for magmas in the Lille Kufjord chamber. Inflexions in the paths mark the appearance of new liquidus phases. Batches of parental magma (P) introduced into the chamber decrease in density as olivine fractionates. In A and B, a derivative magma (D) has attained the same density as the magma resident in the chamber (R), promoting mixing. In C, derivative and resident magmas mix only when they have comparable compositions. Due to solid-solution effects in fractionating minerals, it is unlikely that magmas follow density-differentiation paths consisting of a number of linear segments as depicted here for the sack of simplicity. See the text for further discussion.

le-diffusive convection and short-range crystal settling. Indeed, the thermal regime during double-diffusive convection does not favour growth of primocrysts predominantly in situ unless thermal plumes can transport crystal-free, supercooled liquids from diffusive interfaces to the floor of magma chambers.

The evolution of a basal layer of magma in the Lille Kufjord magma chamber was almost certainly punctuated by episodes of rapid vertical mixing with the overlying liquid layer when their densities were equalized. Viewed from within a basal layer of magma, this simply amounts to abrupt increases in its volume (and thickness). Mixing was, in addition, probably accompanied by changes in magma composition and temperature. Several workers have pointed out that tholeiitic basalts may evolve to a density minimum as olivine and pyroxene are fractionated (Fig. 14a), their densities thereafter increasing rapidly as plagioclase joins the fractionating assemblage and iron is concentrated in residual liquids (Morse 1979, Sparks & Huppert 1984). Magmas in which iron enrichment is balanced by or subordinate to increased concentrations of components with large molar volumes, or indeed did not occur at all, would, however, follow other density paths (Fig. 14). Which of the possible density-composition paths are applicable to the Lille Kufjord magma chamber? An observation that has relevance to this question is the general upward increase in the mg# of olivine through the lower part of LZa (Fig. 3). This suggests a systematic increase in mg# of magmas resident in the chamber with time due to the frequency and relative volume of magma inflow. Such a trend could have been a result of mixing of liquids remaining after partial crystallization of a basal magma layer with the overlying, thermally-convecting main magma which was more differentiated but had the same density. A generalized density-temperature path as portrayed in Fig. 14c would not seem to be appropriate for this process. Two other possible paths are illustrated in Fig. 14. Fig. 14a shows a decrease in magma density while olivine and later olivine and clinopyroxene fractionate. The appearance of plagioclase on the liquidus results in a cusp in the density-compositon curve, more differentiated liquids evolving towards higher density (Sparks & Huppert 1984, Morse 1986). Fig. 14b presents an alternative evolution in that after the appearance of plagioclase the residual liquids maintain a constant density. Both density-composition paths successfully predict mixing of liquids with equivalent densities but different temperatures and compositions, the product being a hybrid whose final compositon would depend on the relative volumes of the two liquids as well as any crystallization which occurs during the mixing event. It can easily be envisaged, however, that the resulting homogeneous liquid would have a higher Mg-

Fe ratio than the liquid initially overlying a denser basal layer.

An alternative hypothesis may be formulated on the basis of the density-temperature path shown in Fig. 14c. In this evolutionary model, mixing is assumed to take place in a turbulent fountain during the emplacement of new magma. As outlined by Campbell & Turner (1986, 1989) the degree of mixing in a fountain can vary with position and time, and the resulting hybrid magmas may form a series of gravitationally-stable layers at the floor of a magma chamber. In the later stages of emplacement, magma which has undergone little or no mixing can flow beneath the hybrid layer. In such a scenario each of the layers of hybrid magma would be heated from beneath and have no tendency to crystallize. Indeed mixing may itself result in hybrids which are superheated (Irvine et al. 1983). The point of interest in the present context is that hybrids produced during fountaining of magma into the Lille Kufjord chamber would have had higher densities than the magma which occupied the chamber before the intrusive event, as well as higher Mg-Fe ratios. Crystallization of the lowest layer would proceed until its density decreased to that of the overlying layer, initiating mixing (Fig. 15). This sequence of events could have occurred a number of times before plagioclase-pyroxene-olivine assemblages eventually crystallized from a hybrid magma of appropriate composition. A consequence of the model is that successive episodes of magma emplacement could lead to further hybridization, the magmas occupying the base of the chamber becoming discontinuously more magnesian with time. There is some mineralogical evidence that hybridization was an important process even in the origin of the olivine cumulates of LZa. Inspection of Fig. 3 will reveal that olivines become more magnesian upwards in the lower part of LZa, not only in macrolayers of pdoC but also in layers of oC. This feature may imply that all LZa cumulates, including the most primitive types, crystallized from hybrid magmas.

In cumulates, abrupt mixing of liquids of significantly different composition (such as in Fig. 14a and 14b) should be recorded as a more or less marked discontinuity in the cryptic layering. Such a discontinuity has been described from cyclic unit 10 in the Eastern Layered Series of the Rhum Intrusion between olivine cumulates and overlying plagioclase-

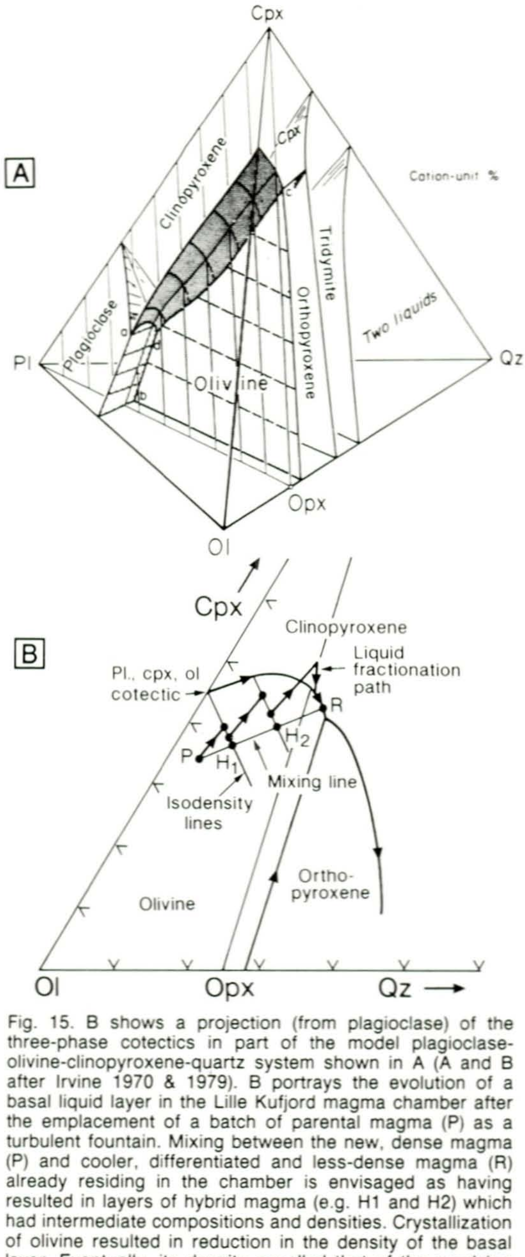

Fig. 15. B shows a projection (from plagioclase) of the three-phase cotectics in part of the model plagioclase-olivine-clinopyroxene-quartz system shown in A (A and B after Irvine 1970 & 1979). B portrays the evolution of a basal liquid layer in the Lille Kufjord magma chamber after the emplacement of a batch of parental magma (P) as a turbulent fountain. Mixing between the new, dense magma (P) and cooler, differentiated and less-dense magma (R) already residing in the chamber is envisaged as having resulted in layers of hybrid magma (e.g. H1 and H2) which had intermediate compositions and densities. Crystallization of olivine resulted in reduction in the density of the basal layer. Eventually, its density equalled that of the overlying hybrid layer (H1) and mixing ensued. The expanded basal layer continued to fractionate olivine both before and after it mixed with liquid layer H2. Further olivine crystallization led the basal magma to saturation in Ca-rich pyroxene and later to plagioclase saturation as it evolved in composition towards that of the derivative magma R. In B density contours are schematic.

olivine cumulates (Tait 1985, Palacz & Tait 1985). In the Lille Kufjord Intrusion breaks in mineral composition are not obvious in macrorhythmic unit 7, though there is a rather sudden change to more iron-rich olivines within the doC macrolayer of unit 10 (see above). The absence of distinct discontinuities is regarded as evidence, albeit negative, for either no mixing of disparate magmas having taken place or mixing of liquids only slightly different in composition.

The evolutionary cycle leading to a macrorhythmic unit of the ideal type as described above could be terminated prematurely at any stage by emplacement of a new batch of high-temperature magma. A new batch of magma may have been emplaced while the basal magma layer remaining from a previous influx was still crystallizing olivine alone. The new basal liquid layer(s) could in this case have mixed with the succeeding layer at an early stage in its differentiation, the crystalline products being olivine cumulates both before and after homogenization. Mixing events of this nature may not be detectable in the resulting sequence of uniform cumulates, though the emplacement of the new batch of magma may be marked by a regression in the composition of olivine (e.g. Irvine 1980). Influx of magma at a somewhat later stage, when the basal layer had differentiated to saturation in clinopyroxene, could elevate this liquid layer. If the temporary floor of the chamber exhibited a sufficiently persistent slope, then the more differentiated liquid could spread over a higher part of the cumulate-magma interface (Irvine et al. 1983, Robins et al. 1987). On the part of the floor overrun by the elevated liquid layer a macrorhythmic unit could be initiated by precipitation of a macrolayer of clinopyroxene-olivine cumulate. As noted above, units of this type are represented in LZa. They may have been generated by this combination of repeated influx, differentiation and a sloping floor. There is no implication that the floor of the Lille Kufjord chamber at any time had steep slopes. Basal liquid layers of the order of tens of metres deep are adequate for the production of the layers of oC in LZa assuming that they reflect fractionation of 10 vol.% olivine, and regular slopes of a few degrees along the half length of the intrusion are all that would be required for this process to occur. At the same time, olivine cumulates could begin to crystallize on the structurally lower parts of the floor of the magma chamber, initiating a new macrorhythmic unit which resided on a unit of the uncompleted type (consisting of oC followed by doC).

A basal layer of magma crystallizing olivine is likely to have been subjected to other types of mixing process than those mentioned above, including assimilation during emplacement of earlier, lower-temperature cumulates forming the temporary floor of the chamber and assimilation of adjacent Marginal Series rocks or xenoliths of wall rocks. These processes would have resulted to varying extent in forcing the introduced magmas along unique compositional paths towards lower density. A high degree of mixing during emplacement and fractional crystallization of new magma is a possible mechanism for the origin of the uncommon macrorythmic units consisting only of macrolayers of oC and pdoC. It seems unlikely, however, that cumulates on the floor or walls of the magma chamber could be assimilated in sufficient volume to alter the sequence of crystallization to the extent required. An alternative and preferred hypothesis appeals to withdrawal of magma from the base of the chamber. This process may have resulted in subsidence of the compositionally-stratified magma column, bringing less-dense, more-differentiated magma to the floor. Thus a layer of olivine-saturated magma resting on the temporary floor of the Lille Kufjord chamber, as well as some of the succeeding layers of more differentiated liquid, may have been withdrawn into an underlying feeder, leaving magma saturated in plagioclase, clinopyroxene and olivine lying on the earlier olivine cumulates.

The draining of magma from the base of a chamber, back into its feeder system, is, as far as the authors are aware, a novel idea which may have widespread application in the interpretation of layered intrusions. It is, however, not without certain analogues in active volcanic areas. The draining of Hawaiian basaltic lavas back into the conduits from which they were erupted has been observed on numerous occasions, but is almost certainly a consequence of the mechanisms of lava fountaining (Decker 1987, Greenland et al. 1988). More significant are the pronounced fluctuations in the levels of long-lived lava lakes, without any connection with extrusive activity, which have been well documented at Kilauea (Jaggar 1947, MacDonald & Abbot 1979). In the plutonic environment, magma standing in a dyke-like intrusion beneath and in hydraulic continuity with a chamber might be rather rapidly withdrawn due to the initiation and propagation of an intrusion lower down the feeder system. A magma chamber from which magma is withdrawn through the floor could respond to such an event by deflation, for instance by subsidence of its roof, or magma may be drawn down into it from conduits extending to a volcanic edifice. General subsidence of the Kilauea area of Hawaii and local collapse within Halemaumau Crater has been attributed to just such a withdrawal of magma from a chamber 3-5 km below the surface and the consequent draining of shallow conduits (MacDonald & Abbot 1979).

Open- system magma chambers like the Lille Kufjord where there is evidence for magma having been both intruded and extracted through the floor can be conveniently referred to as surge-type chambers (signifying that magma is introduced and drained through a common conduit as a result of variations in pressure that are not necessarily periodic and may be transient). Fluctuations in the vertical position of liquid layers in such chambers can be the cause of complex, two- and three-dimensional stratigraphic relationships between cumulate macrolayers. Such relationships occur in the Stillwater Complex (Irvine et al. 1983) and in the Honningsvåg Intrusive Suite (Robins et al. 1987). Irvine et al. (1983) attributed the subsidence of liquid layers in the Stillwater magma chamber to transfer of lower-density residual magma from the lowest layer in the stratified liquid column crystallizing along an inclined cumulate-magma interface. If small angles existed between liquid layers and the floors of magma chambers, as seems likely, then leakage of magma by this mechanism would seem to be inadequate. Its operation does not appear to be supported by experimental evidence (Turner & Gustavson 1978, Huppert & Sparks 1984). We suggest that cumulates in the Stillwater Complex and the Honningsvåg Suite crystallized in surge-type magma chambers in which magma withdrawal was slow enough to be recorded in the cumulates as wedge-shaped macrolayers due to the down-dip migration of crystallization belts characterized by different cumulus assemblages across the floors of the chambers. Drainage and filtration of magma through floor cumulates recently proposed for the origin of thin chromite seams in the Rhum Layered Intrusion (Henderson 1989) may also have resulted from reductions in pressure in an underlying feeder and withdrawal of magm a from the Rhum chamber.

Any attempt to model crystallization at the base of a chamber in which double-diffusive convection was taking place cannot neglect the fate of the magma occupying the bulk of the intrusion. Unfortunately, the evolution of this magma during the relevant interval of time will almost certainly not be recorded in bottom cumulates and an Upper Marginal Series is not preserved for study in the Lille Kufjord Intrusion. Consequently, the available observational data bearing on this question is at best sketchy. The composition of the Marginal Series does, however, suggest that the chamber prior to the crystallization of the LZ cumulates was filled with a relatively-evolved, orthopyroxene-saturated basaltic magma, probably extensively contaminated by assimilation of wall-rock gneiss. In addition, the mineral compositions in the oldest cumulates in LZa, particularly olivines which are apparently the most iron-rich present in LZa and which have compositions similar to those in LZb and the UZ, suggest crystallization from a differentiated magma which was near to saturation in orthopyroxene. The impression of the authors is that the chamber prior to the crystallization of LZa was filled by a magma compositionally akin to that which at a later stage formed the uppermost LZb and UZ cumulates. It is postulated that this magma had been evolving with decreasing density along a liquid line of descent such as that illustrated in Fig. 14c. This may have resulted in compositional stratification of the magma, with less-dense, more-differentiated magma collecting at the roof of the chamber (Turner & Campbell 1986, McBirney et al. 1985). Since the more-differentiated magma resided above hotter magma, it is probable that it was superheated and its buoyancy may well have been enhanced by continuous assimilation of roof rocks. The bulk of the chamber is, however, envisaged as being filled with homogeneous magma whose composition was gradually changing through mixing in of less-dense, differentiated liquid released at the floor (see above). Emplacement of hotter, denser magma at the base of the chamber, initiating the crystallization of the oldest part of LZa, would have led to intensification of convection in the pre-existing magma as well as superheating. Any crystals suspended in magma flowing off the walls of the chamber near the base of the pre-existing liquid column would thus redissolve (Fig. 16).

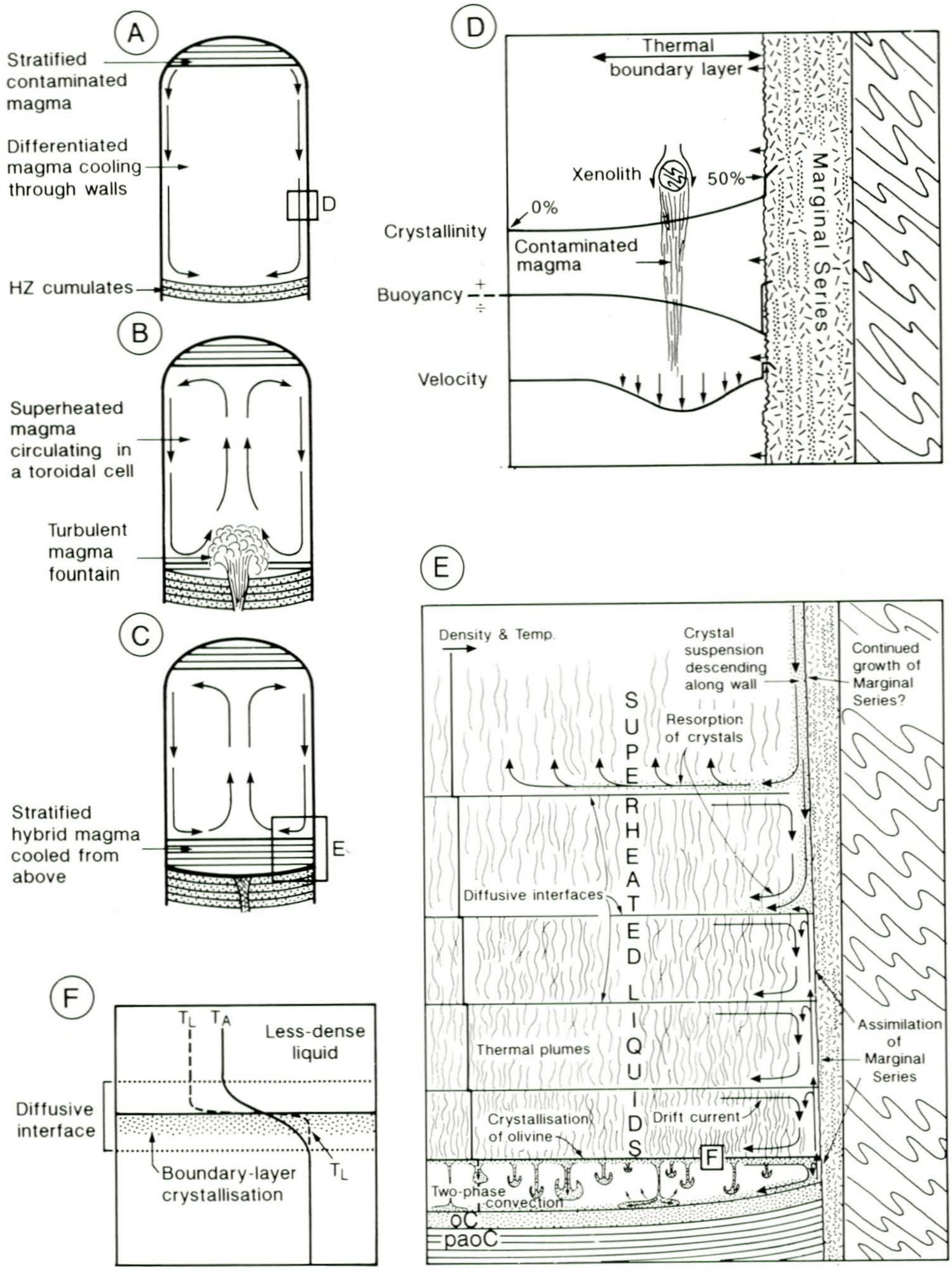

Fig. 16. Magma chamber model (not to scale) derived for the evolution of LZa:
A-C illustrate the fountaining of dense, hot magma into somewhat differentiated, cooler and less-dense magma resident in the chamber. Mixing in the turbulent fountain resulted in a number of independently-convecting layers of hybrid magma over the floor of the chamber.
D depicts the slow growth of the Marginal Series into the thermal boundary layer of the differentiated magma occupying the chamber before the initiation of the events which resulted in the LZa cumulates (see A).
E is an enlarged portion of C and shows the mode of convection envisaged in the liquid layers occupying the lowest part of the magma chamber. Olivine crystallization is portrayed as taking place in the diffusive interface at the top of the layer, with crystals being transported to the floor by two-phase convection.
F shows the temperature gradient in the diffusive interface (curve labelled TA). The variation in liquidus temperatures in the interface is given by curve TL. Olivine crystallization is shown as taking place in the zone where TA is lower than TL. Periodic instability in this zone of slightly elevated density resulted in two-phase convection.

Consequences of the model for the Marginal Series

The Marginal Series as exposed along the western contact of the Lille Kufjord Intrusion appears to have crystallized before rather than at the same time as most of the LZ cumulates. This is demonstrated by the persistent angular discordance between the fabric of the Layered Series and that of the Marginal Series, the lack of rock types in the Marginal Series which may be equated with the olivine and clinopyroxene-olivine cumulates of LZa and the differences in mineral compositions in the Marginal Series and LZ cumulates. The physical model developed above suggests that the lack of any record of LZ crystallization may have resulted from assimilation of the inner part of the Marginal Series. The following sequence of events may have led to this phenomenon:

1. The Marginal Series developed around a chamber filled initially with differentiated magma. A hidden sequence of cumulates was simultaneously precipitated on the floor of the chamber. Cumulates forming the lowest part of LZa which contain relatively low-temperature mineral compositions may represent the latest stages of this early evolution.
2. Repeated influx into the chamber of denser, hotter and more-magnesian magma resulted in a compositionally-zoned magma column. High-temperature magma near the base of the column was able to assimilate the adjacent Marginal Series while crystallizing LZa cumulates on the floor of the chamber (Fig. 16). At the same time, crystallization of the Marginal Series may possibly have continued around the upper part of the chamber which contained cooler, more differentiated magma.
3. As crystallization of LZa proceeded with the periodic injection of new magma, the basal, high-temperature zone of the magma column migrated upwards, assimilating the Marginal Series along its inner contact as it moved. Melting of the inner margin of the Marginal Series was an effective barrier to any crystallization of the high-temperature magmas along the walls of the chamber.

This sequence of events appears to be an unavoidable consequence of recurrent inflow of dense, high-temperature magma into a steep-sided magma chamber. In a larger replenished magma chamber than the Lille Kufjord, rates of cooling and accumulation of bottom cumulates could conceivably have been so low as to permit the complete removal of any marginal series rocks by assimilation.

Melting of the Marginal Series along its inner margins is proposed as the principal mechanism by which the gabbronorite xenoliths found buried in LZ cumulates were derived. The MS was presumably attacked differentially and, as both material and support was removed, blocks of gabbronorite could occasionally avalanche down the walls of the intrusion to its base.

Conclusions

The Lille Kufjord magma chamber was established in complexly-deformed, sillimanite-grade paragneisses during Middle Cambrian crustal extension. Contact-metamorphic mineral assemblages suggest that the Lille Kufjord Intrusion crystallized at pressures of 5.4- 8.2 kb, depending on P_{H_2O}, corresponding to mid-crustal depths. The metamorphic envelope shows evidence of Caledonian deformation and upper greenschist/lower amphibolite-facies metamorphism after contact-metamorphic recrystallization but the Lille Kufjord Intrusion is largely unaffected by these later tectothermal events and retains its original form, orientation and internal structure.

The Lille Kufjord Intrusion consists of a Marginal Series (MS) up to 100m wide and a more than 1400m-thick Layered Series (LS) which crystallized, respectively, on the steep walls and floor of the magma chamber. Layering in the LS is discordant with that in the MS and in the SE half of the intrusion it defines a gentle, symmetrical and upright syncline which is interpreted to be a result of subsidence concurrent with formation of cumulates on the floor of the magma chamber.

The outermost 2-3m of the MS consists of garnetiferous quartz gabbronorite which has a transistional contact with the migmatites in the inner part of the contact-metamorphic aureole; no fine-grained rocks representing chilled magma occur along the margins of the intrusion. The MS is composed of modally- and texturally-layered gabbronorite which contains sporadic olivine as well as pockets and bands of pegmatitic magnetite gabbronorite. Layering is generally subparallel with the external contact of the intrusion and may be either tabular, undulating or corrugated. Pegmatitic bands in the MS are conspicuously asymmetrical in that they are enriched in plagioclase towards the exterior and in pyroxene towards the interior part of the Series. Some pockets of gabbronorite pegmatite show feldspar-rich margins and cores of either coarse-grained granitoid or paragneiss. The MS appears to have crystallized from relatively-differentiated, subalkaline basalt magma, contaminated by assimilation of varying amounts of country-rock paragneiss, which was cooling as it flowed down the margins of the magma chamber.

The LS can be subdivided into a 270m thick Upper Zone (UZ), consisting predominantly of gabbronorite (plagioclase-clinopyroxene-orthopyroxene cumulates) with subordinate layers of olivine gabbronorite, and a 1130m-thick Lower Zone (LZ) in which cumulus olivine is ubiquitous. The upper 750m of the LZ sequence consists exclusively of modally-layered olivine gabbro (plagioclase-clinopyroxene-olivine cumulates) and is designated LZb. The 380m thick LZa exhibits a sequence of cumulates of varied modal composition, including olivine cumulate (oC), clinoproxene-olivine cumulate (doC) and plagioclase-clinopyroxene-cumulate (pdoC). The LZ cumulates are underlain by a Hidden Zone (HZ) of indeterminate, but possibly substantial thickness.

Detailed logging along a traverse (traverse B) through LZa has disclosed 42 lithologically distinct macrolayers (sheet-like entities characterized by a single cumulus mineral or a particular assemblage of cumulus minerals). The principal cumulate types are almost equally represented in terms of numbers of macrolayers but not in total thicknesses: pdoC occurs in 14 macrolayers with a cumulative thickness equalling 63% of the section; oC forms 14 layers with a thickness totalling 22% of the sequence; doC constitutes 13 macrolayers with a thickness corresponding to just 15% of the stratigraphy. Statistical analysis of the frequency of upward lithological transitions reveals that the stratigraphic sequence exhibits a strong first order Markovian property. This is regarded as a persuasive argument for sequential layer formation. The transition analysis forms the rationale for subdivision of the LZa sequence, as developed in the logged section, into 16 macrorhythmic units of different types: The modal (or ideal) unit, containing the sequence oC-doC-pdoC, occurs 8 times; Two uncompleted units, consisting of oC succeeded by doC (and overlain by oC), are represented in the section; Two reduced units, embracing a basal doC macrolayer followed by pdoC, are found in the sequence; The interrupted unit in which oC is succeeded directly by pdoC, occurs 3 times in the section.

The thicknesses of the macrorhythmic units encountered in traverse B vary considerably, as do the relative thicknesses of their constituent macrolayers. Individual units are from as little as 4.9 to a maximum of 53m thick. No correlation appears to exist between the thicknesses of pdoC macrolayers and layers of other types in the individual macrorhythmic units. There is, however, a crude correlation of the thicknesses of oC-doC layer pairs.

Logging of subsidiary sections has revealed that many of the principal features of the stratigraphy of LZa as developed in traverse B are conserved along strike for distances of up to 2.7 km. Nevertheless, there are lateral variations in both the number and thicknesses of macrorhythmic units and changes in the nature of the layer sequences they comprise. There is evidence that bases of units may locally be discordant and some units of restricted lateral extent appear to occupy depressions formed by the removal of underlying cumulates.

Macrolayers of oC are massive but macrolayers of doC and pdoC are generally composed of numerous smaller-scale, modally-distinctive layers up to 1m thick. Boundaries between modal layers are sharp to diffuse and planar, wavy or, in special cases, fingered. In pdoC macrolayers, modally-graded layers commonly alternate with isomodal layers. In the lower parts of several of these macrolayers, where the bulk composition of the cumulates appears to be more mafic than expected for a cotectic assemblage of plagioclase, clinopyroxene and olivine, modal layering appears as repetitions of doC-pdoC or oC-doC-pdoC layer sequences. Boundaries between some doC and succeeding pdoC (and rare poC) layers are conspicuously fingered. Macrolayers of doC are generally characterized by layers grading upwards from oC to doC and sharply-bounded layers of oC and doC.

Electron microprobe analysis of olivine in samples collected through two macrorhythmic units of the modal type have revealed limited but significant cryptic compositional variations (e.g. Fo 72.5-79.7 in MU 10). The bases of the units are regressive discontinuities, the basal olivine cumulate layers containing the most magnesian olivines in the units. Clinopyroxene and plagioclase are, however, zoned to a degree that obscures any systematic compositional variations that may have existed between successive cumulates.

The LZa cumulates are deduced to have crystallized on the floor of a compositionally-layered magma chamber. Horizontal liquid layering was established and maintained by the periodic emplacement of batches of hot, olivine-saturated basalt magma which mixed with and underflowed less-dense, more-differentiated, cooler magma already residing in the chamber. Cumulates were generated exclusively from the lowest of the liquid layers. Primocrysts nucleated and grew in the diffusive boundary layer and were transported by two-phase convection to the floor of the magma chamber where they settled out while the less-dense residual melt was returned to the body of the liquid layer. Olivine cumulates were precipitated from the basal layer after replenishment events. Differentiation of the layer, accompanied by episodes of rapid vertical mixing with the overlying layer when densities were equalized, led to saturation in clinopyroxene and eventually in plagioclase, resulting in the formation of modal macrorhythmic units. The emplacement of new magma occasionally took place prematurely in this cycle of events. Uncompleted units resulted from the emplacement of new magma at a stage after saturation of the basal layer with clinopyroxene but before saturation in plagioclase. Macrorhythmic units of the reduced type are proposed to have been initiated on structurally-high parts of an uneven magma-chamber floor by elevation of the layered liquid column during emplacement events. Thus liquids in equilibrium with plagioclase, clinopyroxene and olivine were displaced by magma from which clinopyroxene and olivine were crystallizing. It is postulated that units of this type were continuous, down the dip of the floor of the chamber, with units of the modal type.

Interrupted macrorhythmic units are interpreted as the result of the rapid withdrawal of magma from the base of the chamber. Withdrawal of magma, probably into a feeder conduit beneath and in hydraulic continuity with the chamber, resulted in subsidence of the liquid layering, bringing differentiated liquid to the floor. The liquid layer from which olivine cumulates were crystallizing, as well as any overlying layers which had compositions such that they had olivine or clinopyroxene as liquidus phases, drained away and were replaced by magma capable of precipitating plagioclase, clinopyroxene and olivine. The concept of surge-type magma chambers like the Lille Kufjord, into which magma was periodically emplaced and occasionally withdrawn through an underlying feeder, is novel and may find wide application in the interpretation of layered intrusions.

The types of cumulates which constitute LZa are not represented in the adjacent MS. This is considered to be a consequence of the existence of high-temperature, stratified liquids at the base of the chamber. These were able to assimilate the gabbronorites forming the inner margin of the MS. At the same time, crystallization of the MS may have continued higher up the walls where the magma chamber was occupied by lower-temperature, more-differentiated magma. Melting of the inner margin of the MS is considered to have resulted in the derivation of the rounded autoliths of gabbronorite found in the LZ cumulates. In a replenished magma chamber larger than the Lille Kufjord, where cooling rates could have been considerably lower, assimilation of any marginal series may have gone to completion.

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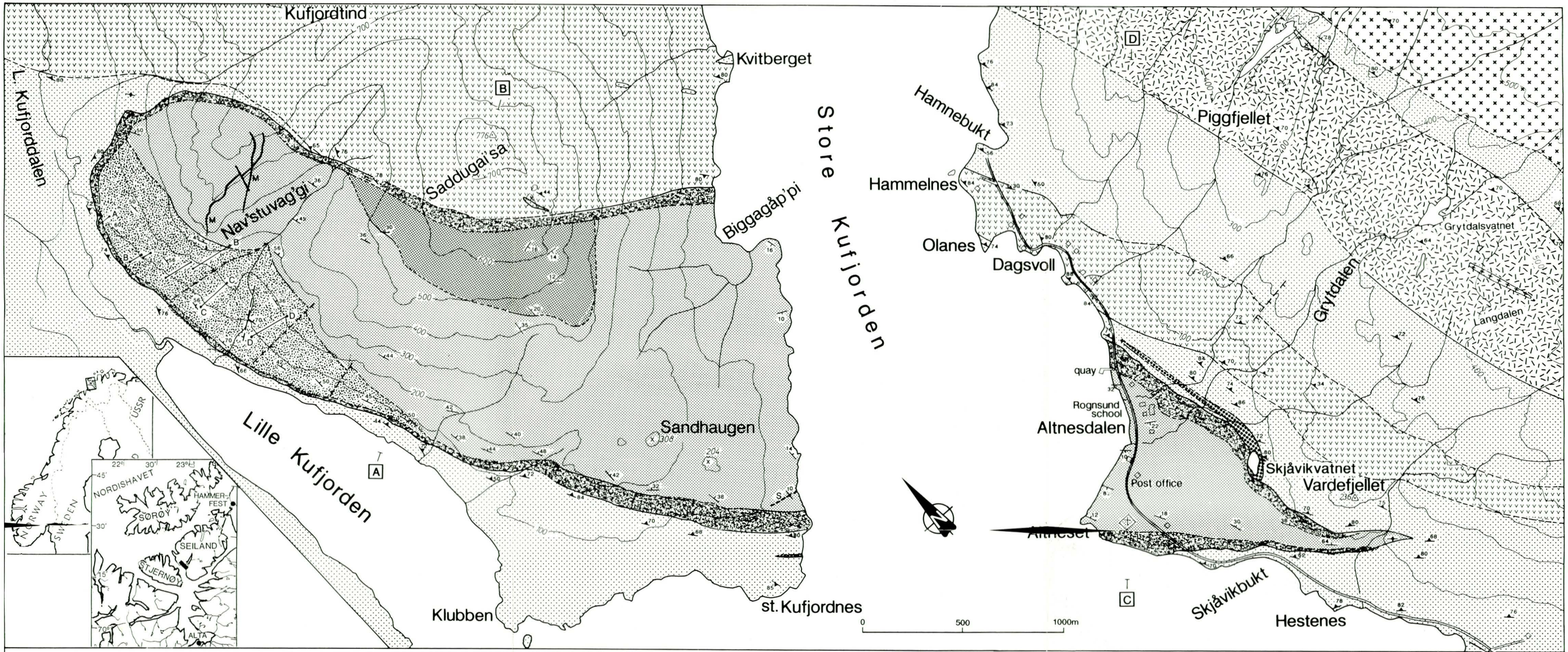
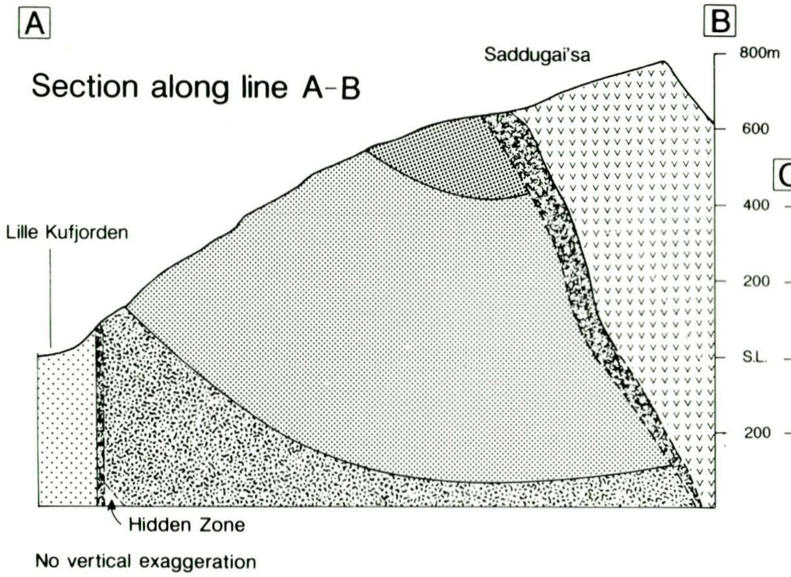
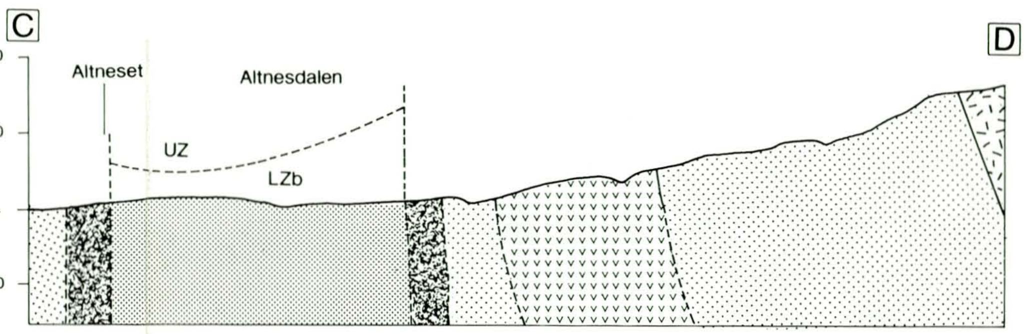
GEOLOGICAL MAP OF THE LILLE KUFJORD INTRUSION







LEGEND

- K-feldspar-ægirine augite-sphene fenite, minor carbonatite.
- Olivine gabbro, ol. melagabbro ol. clinopyroxenite.
- Olivine gabbro, gabbronorite monzonite, perthosite: Seiland Syenogabbro
- Gabbronorite: Olanes Gabbronorite
- Paragneisses, quartzite calc-silicate rocks
- 300 Contour, height in metres
- House, school, foundation

Lille Kufjord Intrusion

- Upper Zone, Gabbronorite
- Lower Zone b, olivine gabbro
- Lower zone a, ol. gabbro, peridotite, ol. clinopyroxenite
- Marginal Series, gabbronorite, ol. gabbro, gabbronorite pegmatite
- Trig. point, spot height, elevations in metres
- Cemetery

Symbols

- Strike/dip of modal layering
- Strike/dip of layering and banding in Marginal Series
- Strike/dip of foliation in meta-igneous rocks and paragneisses
- Dykes. M=mafic, S= syenite
- Faults, ticks on downthrown side
- Geological boundaries, certain, inferred.
- Logged traverse

Topographic base is from Norges Geografiske Oppmåling 1 : 50 000 map sheet 1835 I -Seiland

Compiled by B. Robins in 1989 from mapping by Robins, B., Gardner, P.M., Yurdakul, M. & Gading, M.