High-temperature ultramafic complexes in the North Norwegian Caledonides: I — Regional setting and field relationships

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Four major (25—100 km²) ultramafic complexes were developed in the Sørøy Nappe during the second phase of Finnmarkian deformation in the North Norwegian Caledonides. They were emplaced into layered mafic intrusions and show broadly similar emplacement histories and petrographic variations suggesting a related petrogenesis.

The Nordre Bumannsfjord, Melkvann and Kvalfjord group of ultramafic complexes developed in part by emplacement of both replacive and dilational ne-normative ultramafic sheets and dykes which progressively fragmented the layered olivine gabbro envelope. The earliest dykes and sheets are from a few cm to 100 m wide and show highly irregular, nondilational contacts. They are dominantly coarse-grained, xenolithic olivine clinopyroxenite varying locally to dunite, poikilitic wehrlite, feldspathic olivine clinopyroxenite and olivine melagabbro. Later dykes are from a few cm to 20 m wide and also lack chilled margins but show regular, dilational contact relationships. They include poikilitic wehrlite (commonly spatially associated with veins and patches of secondary wehrlite and dunite), olivine clinopyroxenite, olivine—hornblende clinopyroxenite, hornblende peridotite and hornblende melagabbro. Some members of the dyke suite exhibit mineral lamination, modal layering and cyclic units, and others contain mosaic-porphyroclastic spinel lherzolite nodules. Variably foliated and metamorphosed olivine gabbro, ankaramite and picrite dykes with chilled margins were emplaced during the latest stages in the evolution of the complexes.

The Reinfjord ultramafic complex contains pronounced, subhorizontal modal layering and evidence of at least 3 major magmatic events. The earliest parts of the complex comprise hy-normative wehrlite and olivine clinopyroxenite (olivine and clinopyroxene—olivine cumulates) containing abundant blocks derived from the subalkaline layered gabbro envelope as well as blocks of crudely layered or massive olivine websterite and websterite derived from marginal zones. Plagioclase is present only in marginal zones and in cumulates in the vicinity of gabbro xenoliths. The transgressive core of the complex is composed of dunite and poikilitic wehrlite (olivine cumulate) and is associated with the development of secondary dunite and poikilitic wehrlite from earlier cumulates. The olivine-rich rocks are traversed by dense swarms of veins and dilational dykes of dunite, wehrlite, lherzolite, olivine clinopyroxenite and olivine gabbro as well as amphibole-rich rock types.

The intrusive sequences and petrographic variations represented in the complexes suggest the successive emplacement of mantle-derived magmas with a diminishing number of liquidus phases, accompanied by *in situ* liquid-crystal fractionation, subsidiary hybridization and metasomatism.

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Introduction

The Seiland magmatic province of West Finnmark and North Troms (Roberts 1974, Robins & Gardner 1975) contains a variety of predominantly basic plutonic rocks emplaced during the Finnmarkian phase of the Caledonian orogeny (Sturt et al. 1978). Although the province is dominated by large syn-orogenic layered gabbros, it also contains several major ultramafic complexes in addition to numerous small ultramafic bodies. Early descriptions of the ultramafic complexes include those of Barth (1953, 1961) and Oosterom (1963).

During the last two decades, research on the stratigraphic, structural and metamorphic evolution of the province (Sturt et al. 1975, 1978, Ramsay et al. 1985) and radiometric age determinations (Pringle & Sturt 1969, Sturt et al. 1978) have provided a detailed temporal framework of Finnmarkian events, a major feature of which involved the periodic injection of mantle-derived magmas into the developing orogenic zone (Robins & Gardner 1974, 1975). Although many of the gabbro plutons of the province have been studied in recent years (Hooper 1971, Robins & Gardner 1974, Gardner 1980, Robins 1982), the ultramafic complexes have received little attention, except for the Reinfjord complex in the southwest of the province (Bennett 1971, 1974) and more recently, the Nordre Bumannsfjord complex on western Seiland (Sturt et al. 1980).

Bennett (1971, 1974) showed the Reinfjord complex to be a high-temperature syn-orogenic intrusion characterized by an unusual development of ultramafic cumulates, and suggested that the crude concentric zonation was produced by assimilation of the wall rocks.Because of its thick sequence of plagioclase-free cumulates and its high temperature of emplacement Bennett (1974) suggested that the complex may have crystallized from ultrabasic magmas. Sturt et al. (1980) established that the Nordre Bumannsfjord complex is also a high-temperature syn-orogenic body characterized by extensive wall-rock assimilation and argued that the petrological evolution of this complex (and others in the province, including that at Reinfjord) involved primary, relatively Fe-rich dunite magmas.

Ultramafic complexes resembling those of the Seiland province do not appear to have been reported from elsewhere in the Scandinavian Caledonides (Stephens et al. 1985). Discordant ultramafic bodies involving rock types varying from dunite to clinopyroxenite are common within the Lyngen gabbro but are an order of magnitude smaller (Randall 1971), and the gabbro itself appears to be an ophiolite fragment (Furnes et al. 1980, 1985). According to Curry (1975) the Honningsvåg ultrabasic complex, emplaced into Silurian metasediments within the Magerøy Nappe of northernmost Norway, was intruded at a late stage in its development by xenolithic dykes and sheets varying from dunite to olivine melagabbro. Recent investigations by one of the authors (B.R.) show, however, that the ultramafic rocks are olivine—chromite cumulates forming either the basal parts of megacyclic units or the matrix to intrusion megabreccias which resulted from the disruption of pre-existing cumulates within a magma conduit.

In this paper, we report results from recent studies in the Melkvann, Nordre Bumannsfjord and Kvalfjord ultramafic complexes in the northeastern part of the Seiland province and attempt to show that they share sufficient similarities in relative ages, geological setting, petrological variations and intrusive relationsships, for them to be regarded as a cogenetic group. Their characteristics are compared with the Reinfjord complex where recent re-investigation suggests that while the Reinfjord intrusion remains unique in its extensive development of layering, its petrogenesis may well be related to that of the ultramafic complexes of Seiland and Stjernøy.

Regional setting of the ultramafic complexes

The regional structural framework

The ultramafic intrusions of the West Finnmark and North Troms are confined to the Sørøy Nappe, which is the uppermost tectonic unit within the Kalak Nappe Complex (Fig. 1), a group of thrust nappes constituting the Finnmarkian allochthon of the northern segment of the Scandinavian Caledonides (Ramsay et al. 1985). Immediately to the east of the Seiland magmatic province the Kalak Nappe Complex is thrust over Karelian metasediments and metavolcanic rocks (the Raipas suite of Reitan (1963) or Raipas Supergroup of Pharaoh et al. (1983)), with a thin autochthonous/parautochthonous cover of Vendian tillite, quartzite and slate preserved in places beneath the lower boundary of the nappe complex (Roberts & Fareth 1974, Pharaoh et al. 1983). The thrust boundary represents a profound discontinuity, bringing the complexly-deformed, amphibolite-facies rocks of the Sørøy Nappe above the weakly metamorphosed and structurally simple Karelian rocks and their Caledonian cover sequence exposed in the Komagfjord and Altafjord tectonic windows (Fig. 1). Further to the east the Kalak Nappe Complex overrides the Gaissa, Jerta and Laksefjord Nappes of low metamorphic grades and traditionally regarded as parautochthonous (but see discussion in Ramsay et al. 1985). Southwestwards the Kalak Nappe Complex is progressively excised by higher nappes forming the late Silurian, Scandian allochthon.

The Kalak Nappe Complex includes both far-travelled and less far-travelled nappes (the distal and proximal allochthons of Ramsay et al. 1985) varying in metamorphic grade from lower greenschist facies in the lowest (proximal) nappes to upper amphibolite facies in the hig-

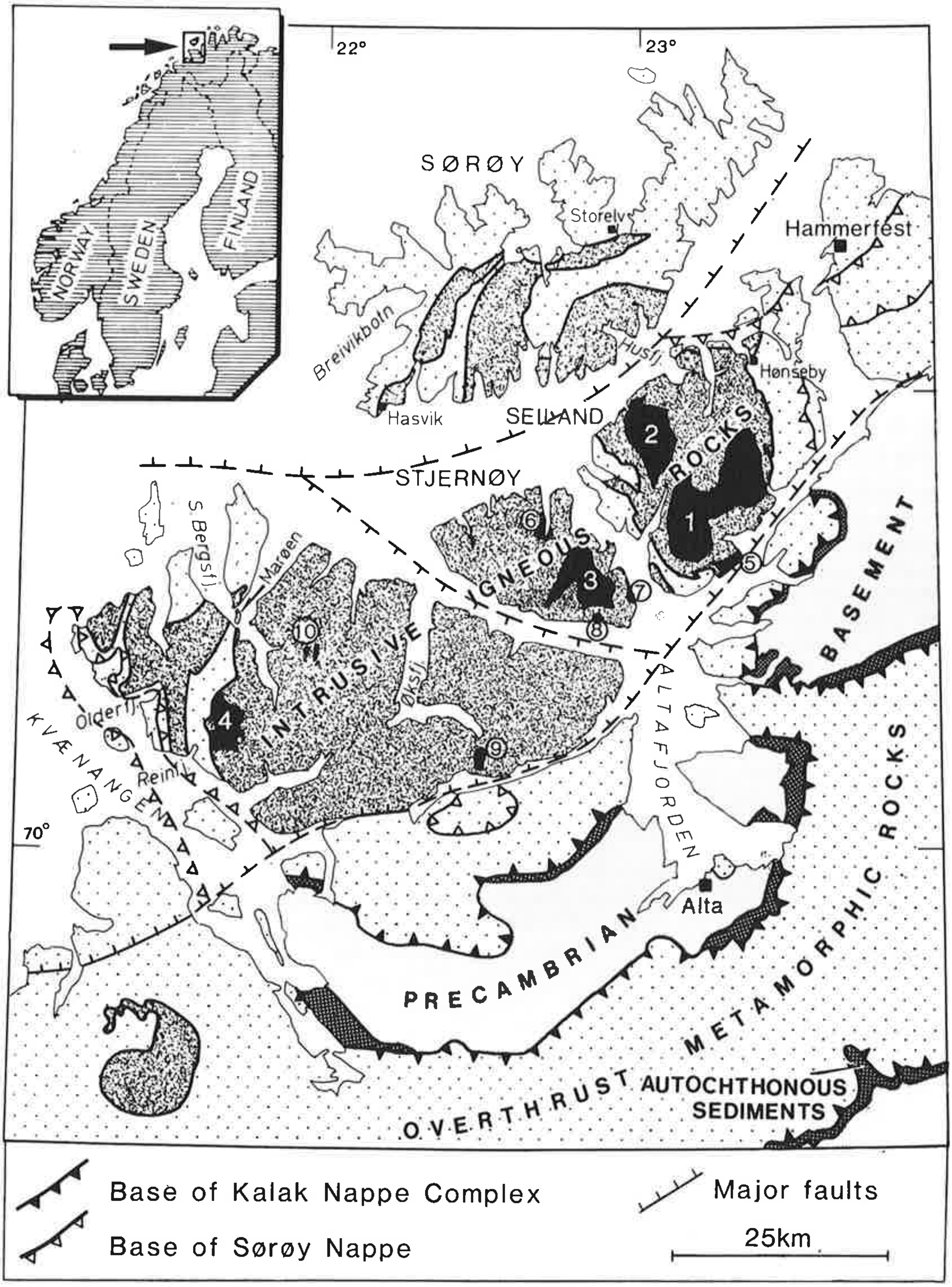

Fig. 1. Location and major tectonic features of the Seiland magmatic provice.
Major ultramafic complexes (shaded black) are: 1. Melkvann; 2. Nordre Bumannsfjord; 3. Kvalfjord; 4. Reinfjord.
Other ultramafic intrusions are: 5. Habuvarri (Happofjell); 6. Kjerringfjord; 7. Hallarbukta (Havnbukt); 8. Nordbukt; 9. Tappeluft; 10. Tverrfjorddalen.

hest (distal) nappes. The nappes typically repeat stratigraphic couplets, in which the lower unit is either pre-Karelian gneiss or the Karelian rocks of the Raipas Supergroup, while the upper unit consists of either Karelian rocks or late Precambrian—Cambrian metasediments. Primary unconformities between the two units are preserved locally (Ramsay & Sturt 1977, Ramsay et al. 1979, 1985). The Sørøy Nappe, containing the Seiland magmatic province, is the uppermost distal allochthon and is characterized by a couplet of pre-Karelian gneiss and Caledonian metasediments which were clearly derived from an ensialic sedimentary basin and its Precambrian gneissic basement.

The tectonothermal evolution of the Sørøy Nappe

The lower stratigraphic unit of the Sørøy Nappe exposed along the southern and eastern part of its present-day outcrop, comprises Precambrian paragneiss including feldspathic biotite schist, quartzite, pelitic gneiss and garnet gneiss (Akselsen 1980). The overlying Caledonian cover sequence consists of a metasedimentary sequence (Ramsay 1971, Roberts 1974), recording a transition from predominantly shallow-water clastic deposition to turbidite-type sedimentation in a sequence has been dated as early Middle Cambrian and younger on the basis of archaeocyathids identified in limestone (Holland & Sturt 1970, but see Debrenne 1984 for a contrary view).

Caledonian deformation within the Sørøy Nappe took place during two protracted phases (D_1 and D_2), each initiated by episodes of strong folding and thrusting which were followed by periods characterized by flattening strains (Ramsay & Sturt 1963, Ball et el. 1963, Roberts 1968, Ramsay 1971, Sturt et al. 1978), possibly related to gravitational spreading following nappe translation (Ramsay et al. 1985).

The amphibolite-facies peak of the Barrovian regional metamorphism in the Caledonian cover sequence was attained between the major deformational phases and metamorphic temperatures gradually waned throughout D_2 (Roberts 1968, Sturt & Taylor 1972, Sturt et al. 1978) (Table 1). The D_1—D_2 growth of garnet, staurolite, kyanite and sillimanite was accompanied locally by the development of migmatites. In the Precambrian basement within the central portions of the Seiland magmatic province the D_1—D_2 regional metamorphic parageneses appear to belong exclusively to the sillimanite zone, and amphibolite-facies conditions persisted well into D_2 (Robins 1971). Here, the local development of granulite-facies parageneses in metasediments (Barth 1953, 1961, Krauskopf 1954, Oosterom 1963) is a consequence of the superimposition of contact and regional metamorphism.

With the exception of the late-stage alkaline suite and associated intrusions, the igneous rocks of the Seiland province generally show the imprint of cooling at intermediate pressure (6—10 Kb). This is expressed by the development of pyroxene—spinel symplectites in olivine-bearing gabbro (Oosterom 1963, Gardner & Robins 1974, Robins 1982) and the formation of garnet—quartz coronas between Ca-poor pyroxene and plagioclase (Akselsen 1980, Gardner 1980).

The detailed emplacement history of the Sørøy Nappe is ambiguous. Pre-D_2 mylonites present along the base of the nappe (Worthing 1971, Akselsen 1980) and the folding of the nappe boundary by major D_2 folds (Akselsen 1980) suggest syn-D_1 translation (Ramsay et al. 1985). The lower metamorphic grade of Caledonian cover sequences within underlying nappes points to final emplacement either during the D_2 phase of Finnmarkian deformation or the subsequent Scandian orogenic phase (Ramsay & Sturt 1977, Ramsay et al. 1985). Emplacement at a late stage in the orogenic evolution is also suggested by the 40 km separation of the surface expression of the Seiland magmatic province from its associated + 100 mgal Bouguer gravity anomaly (Brooks 1966, 1970). Reverse faults and thrusts are also known to have affected the alkaline suite and carbonatites which constitute the latest major intrusions in the Seiland province (Skogen 1980, Bruland 1980, Robins & Tysseland 1983).

The magmatic history of the Seiland province

The emplacement of the high-temperature ultramafic complexes occurred at a relatively late stage in the protracted evolution of the Seiland province (Table 1). The magmatism in the province, which gave rise to predominantly basic, ultrabasic and alkaline rocks, commenced during the first phases of Finnmarkian deformation (D_1) and continued through the D_1—D_2 peak of regional metamorphism and the second phase of deformation (D_2) (Robins & Gardner 1975).

DEFORMATION			REGIONAL METAMORPHISM	MAJOR INTRUSIONS S.W.	MAJOR INTRUSIONS N.E.	RADIOMETRIC AGES *
FINNMARKIAN OROGENY	Late Phase	Localized folding and thrusting	Greenschist facies			
		Extensional tectonics ?	Retrograde metamorphism		Alkaline pyroxenite, alk.syenite[3] ne.syenite[4] carbonatite, fenite	[4]480-491 Ma (K-Ar, nepheline) [3]490 ± 27 Ma (Rb-Sr w.r. isochron)
	Second Phase D 2	Flattening strains (gravitational spreading?)		REINFJORD U.C. Langstrand gabbronorite	N. BUMANNSFJORD, KVALFJ., MELKVANN U.C. Olivine gabbros	
		Cylindrical folds, E. vergence Thrusting			Gabbronorite, perthosite	
			Barrovian amphibolite facies (garnet, staurolite, kyanite, sillimanite)	Sandland - Middagsfj. - Olderfjord gabbronorite	Diorite, monzonite, qtz. syenite Hasvik gabbronorite[2]	[2]528 ± 27 Ma [2]530 ± 16 Ma (Rb-Sr w.r. isochrons)
	First Phase D 1	Flattening strains (gravitational spreading?)	Prograde metamorphism		Breivikbotn,[1] Storelv - Husfjord, Hønseby gabbronorites	[1]540 ± 17 Ma (Rb-Sr w.r. isochron)
		Large-amplitude folds, variable vergence Thrusting	Greenschist facies			

$* \lambda\, ^{87}Rb = 1.42 \times 10^{-11}\, a^{-1}$

Table 1. **Summary of the tectonic, metamorphic and magmatic evolution of the Seiland province. Radiometric ages are quoted from the followed sources: 1. Sturt et al. (1978). 2. Pringle & Sturt (1969), Sturt et al. (1978). 3. Sturt et al. (1978). 4. Sturt et al. (1967). For other references see Robins & Gardner (1975) and text.**

Pre-D_2 gabbroic intrusions are widespread in the province and typically form thick extensive sheets, steep-sided dyke-like bodies or crudely lens-shaped or lopolithic plutons emplaced in both the Caledonian cover sequence and its Precambrian basement. These intrusions include the Storelv—Husfjord and Breivikbotn gabbronorites on Sørøy (Stumpfl & Sturt 1965, Sturt & Ramsay 1965, Speedyman 1983, Sturt & Taylor 1972) and the Hønseby gabbronorite on Seiland (Worthing 1971, Roberts 1974) all of syn-D_1 age, as well as the Hasvik gabbronorite on Sørøy (Robins & Gardner 1974, 1975, Gardner 1980) and the Sandland—Middagsfjell—Olderfjord gabbronorite in the Kvænangen—Bergsfjord area (Hooper 1971) of D_1—D_2 age. In several of the bodies cumulate structures and textures are well preserved and some intrusions exhibit extensive cryptic variation. They are uniformly of subalkaline aspect (Robins & Gardner 1975, Stephens et al. 1985). On Sørøy some of the pre-D_2 basic intrusions are spatially associated with a suite of calc-alkaline intrusions including high-K diorite, monzonite and quartz syenite (Robins & Gardner 1975).

Syn-D_2 activity in the southwestern part of the Seiland province continued with the emplacement of subalkaline basalt magmas (Robins & Gardner 1975). Both the small Marøen gabbro (Gronow 1967) and the major Langstrand layered gabbronorite (Bennett 1972, 1974) possess tholeiitic characteristics, though the latter contains abundant xenoliths of highly-metamorphosed paragneiss and its fractionation trend may possibly have been controlled by assimilation. The Langstrand gabbronorite is intruded by the Reinfjord ultramafic complex, described in the following text.

In the eastern part of the Seiland province the earliest major magmatic event during D_2 resulted in the emplacement of large, generally strongly deformed gabbros associated with syenite (perthosite) fractionates (Robins & Gardner 1974, 1975). These were followed by the emplacement of large plutons of olivine gabbro (the clinopyroxene gabbros of Robins & Gardner (1974)) characterized by thick cumulate sequences containing aluminous diopside or salite, the absence of primary Ca-poor pyroxene and the early appearance of cumulus Fe—Ti oxides. The mineralogy and chemistry of these cumulates are consistent with the fractional crystallization of alkaline olivine basalt parents (Robins & Gardner 1974, Robins 1982). The contacts of the olivine gabbros are generally concordant with the fabric of the host rocks. The latter, and the modal layering within the plutons themselves, dip in most cases towards the centres of the plutons and define deep synforms. The structures are suggestive of gravitational collapse accompanied by viscoelastic deformation of the country rocks (Robins 1971, Petraske et al. 1978). The olivine gabbro plutons are the loci of emplacement of the Seiland—Stjernøy group of ultramafic complexes. The Langstrand gabbronorite has a similar form to that of the olivine gabbros, and here also the southwestern part of the body is intruded by the Reinfjord ultramafic complex.

While the Reinfjord ultramafic complex appears to represent the last major intrusive event in the southwestern part of the Seiland province, the Seiland—Stjernøy ultramafic complexes were postdated by the Lille Kufjord intrusion, a small subalkaline layered body occupying an anomalous position in the magmatic history (Robins & Gardner 1974, 1975, Robins 1982). Members of an alkaline picrite—ankaramite—Mg-rich alkaline olivine basalt dyke swarm cross-cut both the Lille Kufjord intrusion and the Seiland—Stjernøy ultramafites and are widely developed in the eastern and northern parts of the province (Robins & Takla 1979). Some dykes belonging to this widespread, and in places dense, swarm contain spinel lherzolite nodules of mantle derivation (Robins 1975).

The youngest magmatic events represented in the northern and eastern parts of the province led to the emplacement of a suite of alkaline rocks and carbonatite in the form of isolated dykes and major complexes. The alkaline suite includes alkaline pyroxenite, nepheline-free and nepheline-bearing hypersolvus syenites and syenite and nepheline syenite pegmatites (Heier 1961, Sturt & Ramsay 1965, Robins 1972, 1974, 1980). The alkaline suite and carbonatite intrusions were weakly to intensely deformed during a late expression of the D_2 phase of deformation (Sturt & Ramsay 1965, Skogen 1980, Robins & Tysseland 1983) under conditions of lower amphibolite facies to upper greenschist facies metamorphism (Ramsay & Sturt 1970, Skogen 1980). The latest metamorphic effects in the province were the local development of zeolite-facies parageneses in nepheline syenite (Bruland 1980.

The absolute age of magmatic events in the Seiland province

The radiometric ages listed in Table 1 suggest that magmatic activity took place in the Seiland province during middle Cambrian to early Ordovician (Arenig) time. On the basis of the relative age sequence, established on purely geological criteria, the ultramafic complexes would appear to have been emplaced between 530 ± 16 Ma and 490 ± 27 Ma.

Plate-tectonic setting of the Seiland province

Until recently, palinspastic reconstructions of the early-Caledonian evolution of the Seiland province (Ramsay 1973, Robins & Gardner 1975, Sturt et el. 1978), although differing significantly in detail, emphasized the transition from a late Precambrian—Cambrian rifted continental margin to a subduction-dominated regime. Finnmarkian deformation, metamorphism and the magmatic activity represented within the Seiland province were related in these models to persistent eastward subduction of oceanic crust beneath a Baltic plate. The recognition of pre-Ordovician ophiolite fragments in the highest allochthonous units at several places along the length of the Norwegian Caledonides (Furnes et al. 1980, 1985) has, however, highlighted substantial deficiencies in these models and Sturt et al. (1983) have suggested that initial subduction in the middle to late Cambrian had a westward polarity, uplift of the Finnmarkian orogenic belt coinciding with, or succeeding, a changeover to eastward subduction. While a number of features of the Finnmarkian orogenesis in the type area can be rather neatly explained within this plate-tectonic framework, including the internal deformation, P-T paths and displacement of tectonotratigraphic units, as well as ophiolite obduction (Sturt 1984), the interpretation of the magmatism in the Seiland province remains largely enigmatic. Although the detailed plate-tectonic setting of the Seiland magmatic province is as yet very poorly constrained, the magmatism is still regarded in a broad sense as related to the evolution of a destructive plate margin. The alkaline igneous rocks and carbonatites do, however, tend to suggest a period of extensional tectonics during the latest phases of the evolution of the Finnmarkian orogen (Table 1).

Field relationships in the ultramafic complexes

The ultramafic complexes within the Seiland magmatic province fall naturally into two groups on the basis of their spatial relationships, internal structure, host rocks and petrography. The ultramafics exposed on the islands of Seiland and Stjernøy form a coherent group with individual complexes separated by no more than about 7 km. These include the Nordre Bumannsfjord (Sturt et al. 1980), Melkvann (Robins 1971) and Kvalfjord complexes (Oosterom 1963), occupying areas ranging from 30 km^2 (Kvalfjord) to 50 km^2 (N. Bumannsfjord) and possibly more than 100 km^2 (Melkvann), as well as substantially smaller intrusions at Habuvarri (Happofjell) in the southeasternmost part of Seiland, Kjerringfjord on the north coast of Stjernøy, Tudvik between Lille Kvalfjord and Hallarbukta (Havnbukt) on the east coast of Stjernøy and Nordbukt on the south coast of Stjernøy (Fig. 1). Each one of these occurrences is emplaced discordantly in layered olivine gabbro plutons, although the ultramafic rocks in places cross-cut the margins of the gabbros and come into contact with other, older host rocks. The main ultramafic rock type is coarse-grained olivine clinopyroxenite containing variable amounts of plagioclase and amphibole. This is accompanied by smaller volumes of wehrlite and dunite as well as pyroxene—hornblende peridotite and other amphibole-rich ultramafic rocks, olivine melagabbro and hornblende gabbro. Petrographic variations within the bodies are generally highly irregular, and associated ultramafic dykes emplaced in gabbro are common. Although the major ultramafic complexes in the Seiland—Stjernøy region are emplaced into physically separate gabbroic intrusions, these belong to a single, distinctive petrographic suite believed to have resulted from the intrusion and fractional crystallization of critically—undersaturated basalt magma (Robins & Gardner 1974, Robins 1982). As outlined earlier, this group of ultramafic complexes was affected by similar magmatic and metamorphic events subsequent to their development and it is considered reasonably certain that they were emplaced contemporaneously. From the close spatial and temporal association of these ultramafic complexes it follows that any major petrogenetic synthesis erected on the basis of observations within one complex should be equally applicable to the others.

The Reinfjord complex (Bennett 1971, 1974) is situated some 50 km to the southwest of the Seiland—Stjernøy ultramafic plutons and crops out over an area of about 25 km^2 (Fig. 1). The only other ultramafic bodies known in this part of the Seiland province are much smaller, dyke-like occurrences exposed in Tverrfjorddalen between the Svartfjell and Øksfjord ice caps (Hooper 1971). The Reinfjord complex, emplaced into the Langstrand layered gabbronorite, contains pronounced modal layering. Wehrlite and dunite are the principal rock types in the complex, and these are accompanied by olivine clinopyroxenite,lherzolite, feldpathic peridotite, pyroxene-rich ultramafites and olivine melagabbro. Ultramafic dykes cutting the host gabbro or gabbro enclaves are rare and the main petrographic variations within the complex are related to megacyclic units, small-scale modal layering, the vicinity of contacts with the enclosing gabbro or garnet gneiss and a gross zonal structure. Due to the geographic separation of the Reinfjord complex from the Seiland—Stjernøy group of intrusions, its emplacement into a petrographically different host gabbro and the absence in this area of the characteristic late-stage magmatic events represented in the northern and eastern parts of the Seiland province, its contemporaneity with the other ultramafic plutons cannot be demonstrated with any exactness. All the ultramafic complexes were, however, emplaced during the course of the D_2 deformational phase, and it would seem highly probable that they represent a unified magmatic event.

The field relationships and petrography of the individual ultramafic complexes of the Seiland province are summarized in the following sections. The descriptions of the Kvalfjord and Nordre Bumannsfjord complexes are based on the earlier work of Oosterom (1963) and Sturt et al. (1980), supplemented where appropriate by the authors own observations in these intrusions. The petrographic terminology employed is based on Streckeisen (1976).

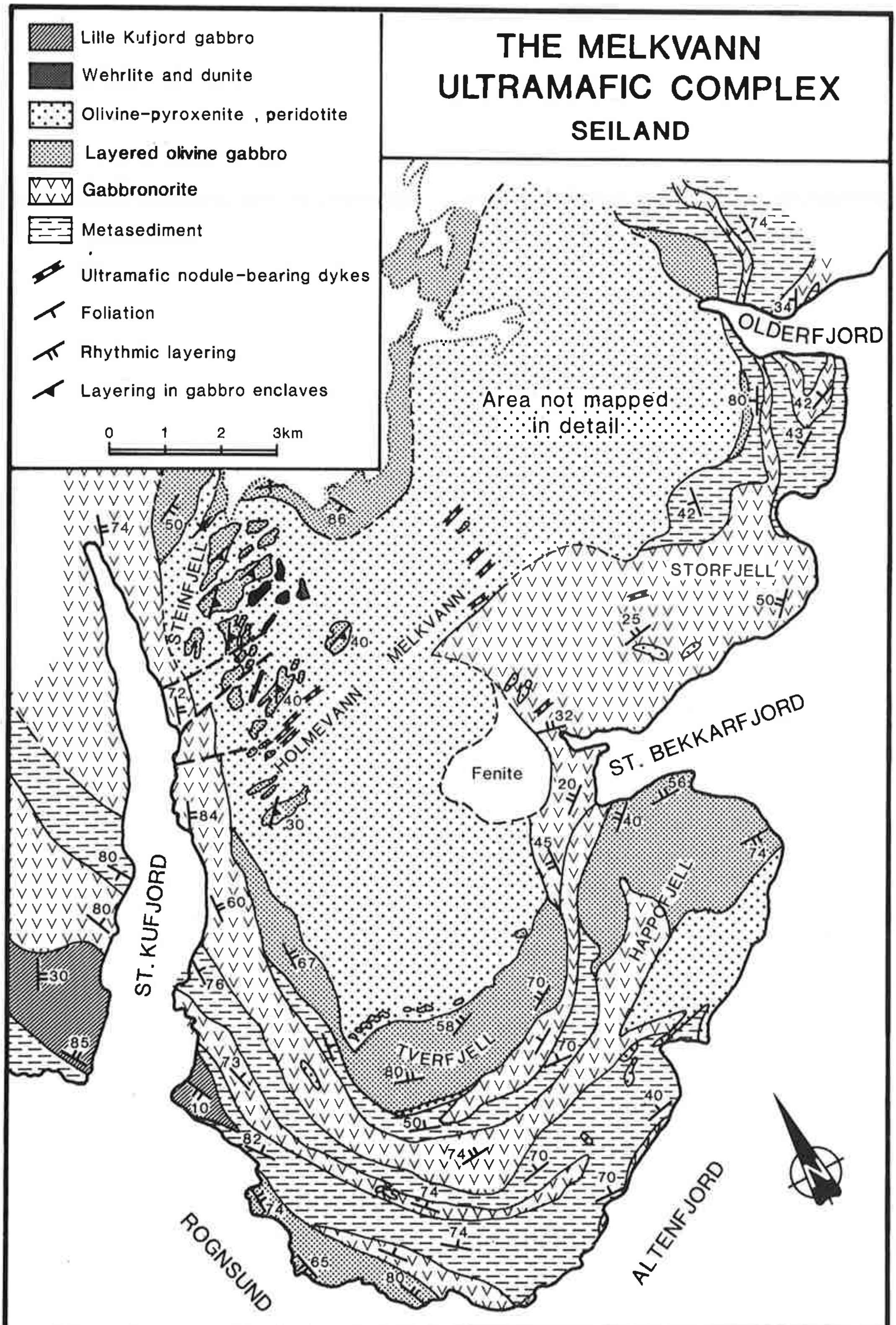

Fig. 2. Simplified geological map of the Melkvann ultramafic complex and its envelope.

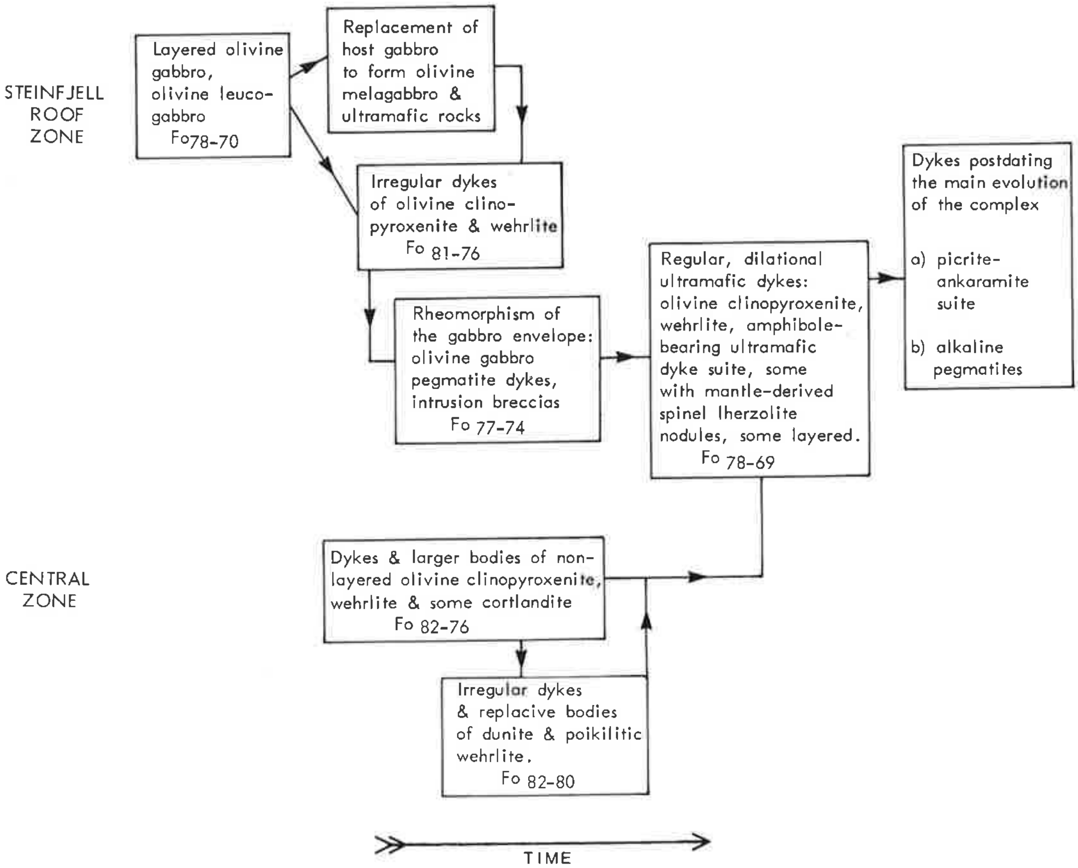

Fig. 3. Intrusive sequences in the central and roof zones of the Melkvann ultramafic complex (based largely on Yeo 1984). Olivine compositions by electron microprobe analysis.

The Melkvann ultramafic complex

The Melkvann complex occupies an area of some 100 km^2 in the southern part of the island of Seiland and is emplaced into a formerly extensive layered olivine gabbro, the remnants of which are preserved in places around the margins of the complex, and as enclaves within it (Figs. 1 & 2). The body lies in the core of a large doubly-plunging synform, the southern closure of which is locally overturned. The synform is defined by S_2 foliations in early—D_2 gabbronorite sheets interbanded with gneissic metasediments and by the modal layering in the syn—D_2 olivine gabbro, which locally contains a recrystallised fabric subparallel to the layering. The ultramafic rocks lack a systematic penetrative foliation, the most conspicuous structural element within the complex being a prominent set of steeply northerly-dipping joints.

The outcrop of the complex forms two lobes linked by a comparatively narrow ultramafic outcrop extending from Melkvann to the southern ice front of Seilandsjøkelen. Along parts of its western and much of its eastern margins, ultramafic rocks extend beyond the confines of the olivine gabbro and intrude older gabbronorite (the Seiland syenogabbro of Robins & Gardner (1974) and in Olderfjord, ultramafic rocks are in contact with gneissic metasediment (Fig. 2). One km west of St. Bekkarfjord, rocks of the ultramafic complex are strongly fenitized. This alteration is associated with the emplacement of magnetite—apatite hornblende clinopyroxenites, one expression of the late-D_2 alkaline activity, which elsewhere in the complex and its envelope produced en échelon swarms of east-northeasterly trending dykes and small plugs of syenite and nepheline syenite pegmatite.

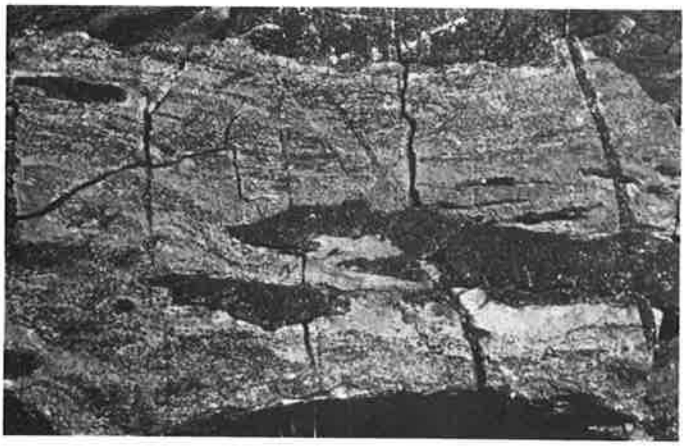

Fig. 4. Boulder derived from a dyke of inhomogeneous, xenocrystic wehrlite grading in place into dunite and containing blocks of coarse-grained olivine clinopyroxenite. The alignment of the xenoliths and the crude banding suggest flowage of a viscous crystal mush. Melkvann u.c., southeast of Steinfjell.

In general, contacts of the complex with its country rocks are discordant, subvertical or steeply inward dipping, but are generally poorly exposed. In a number of places the contacts are seen to be transitional, comprising subvertical sheeted complexes some 300 m wide, in which dyke frequencies increase gradually towards the complex. In several places 10—20 m wide dyke of hornblende—olivine melagabbro, in which amphibole and plagioclase form large oikocrysts, extend obliquely several hundreds of metres from the sheeted contacts.

At Olderfjord erosion has provided a vertical section through the complex of nearly 900 m but over much of the complex the topography lies between the 300 and 800 m contours. Remnants of layered olivine gabbro occur on the high ground of Tverrfjell and are preserved as large enclaves invaded by ultramafic dykes and sheets. Similarly, layered olivine gabbro occurs as dissected screens and irregular enclaves on Steinfjell, and on crests of ridges extending up to 3 km inland from the western contact south of Steinfjell (Fig. 2). Here, enclaves occur only at elevations above 400 m. The attitude of the modal layering within the screens and enclaves is systematically related to the orientation of the layering in the olivine gabbro envelope. This consistent relationship suggests that the enclaves represent 'in-situ' relics of a previously more extensive gabbro body preserved at a structural level close to the local roof of the ultramafic complex.

Although the high temperature of emplacement of the ultramafic complex can be inferred from field relationships implying partial melting, remobilization and assimilation of the olivine gabbro in enclaves and along the margins of the complex, similar effects are not readily observed at contacts with older gabbronorite or metasediment, but this may simply be because these contacts are generally not well exposed. At Olderfjord, metasediment in contact with plagioclase-bearing hornblende clinopyroxenite contains a low- to medium-pressure pyroxene granulite paragenesis, but does not display evidence of extensive partial melting. The adjacent ultramafic rocks do, however, contain small, rounded inclusions of quartz mantled by coronas of fibrous green amphibole. Elsewhere, metasediments show local D_2 superimposition of thermal metamorphism to pyroxene—granulite facies on regional metamorphic assemblages of the almandine — sillimanite — orthoclase subfacies, with the development of extensive rheomorphic breccias. It is not possible, however, to demonstrate that these contact metamorphic effects are due solely to the emplacement of the ultramafic complex, and they are proably due to the combined thermal effects of the complex and its olivine gabbro envelope.

The ultramafic rocks of the Melkvann complex are medium- to coarse-grained and show considerable modal variation involving olivine, clinopyroxene, amphibole, calcic plagioclase and spinel. The central parts of the complex contain an extremely complicated sequence of crosscutting ultramafic intrusions and modal layering is generally absent. The later intrusive events are represented by a sequence of ultramafic dykes, which in places constitute more than 50% of individual outcrops and which have disrupted earlier ultramafic bodies, obscuring their original form. In the roof zones of the complex

Fig. 5. Irregular patches and veins of secondary wehrlite and dunite developed from olivine clinopyroxenite close to discrete wehrlite dykes. Melkvann u.c., southeast of Steinfjell.

preserved on Steinfjell and Tverrfjell (Fig. 2), exposure is generally excellent and here it is apparent that the complex developed through a protracted process of dyke and sheet emplacement, accompanied by mechanical disruption, partial melting, remobilization and assimilation of the olivine gabbro envelope. The sequence of intrusive events in the central and roof zones is summarised in Fig. 3.

Within the central parts of the complex, olivine clinopyroxenite is the main rock type and forms the host to later generations of ultramafic dykes. Locally it grades through an increase in modal olivine into wehrlite (and less commonly dunite), and through increases in amphibole and plagioclase into a variably feldspathic olivine—hornblende clinopyroxenite. The latter rock type is more characteristic of marginal zones of the ultramafic complex where it is usually xenolithic, containing blocks derived from the olivine gabbro envelope, and less frequently, olivine-rich ultramafic xenoliths. Conspicuous dykes and irregular bodies of wehrlite and dunite up

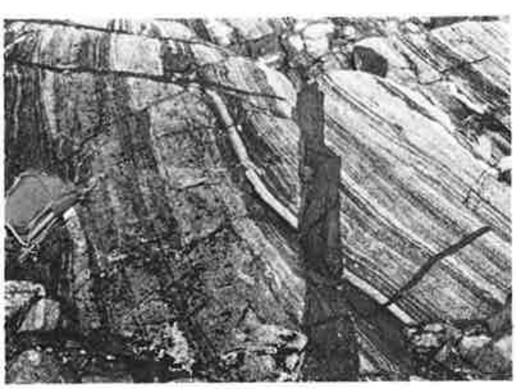

Fig. 6. Modally-layered olivine gabbro cut by narrow, dilational wehrlite dykes. From an enclave within the Steinfjell roof zone, Melkvann u.c.

to 200 m across emplaced in olivine clinopyroxenite occur in a topographic depression 1—2 km southeast of Steinfjell (Fig. 2). In these the clinopyroxene is oikocrystic and locally dunite grades into poikilitic wehrlite enclosing discrete subrounded blocks of coarse olivine clinopyroxenite (Fig. 4). Small-scale layering, defined by variations in the modes of olivine and picotite has been observed in one dunite body, and would seem to indicate a magmatic origin through cumulus processes, but the haphazard distribution of small, irregular patches of wehrlite and dunite in adjacent, relatively homogeneous olivine clinopyroxenite (Fig. 5) suggests that some wehrlite and dunite has developed by replacement of olivine clinopyroxenite.

In the roof zones on Tverrfjell and Steinfjell, olivine clinopyroxenite is the most abundant ultramafic rock type, but plagioclase-bearing wehrlite, olivine melagabbro and gabbro occur in significant volumes, but never as large homogeneous bodies. Small segregations and patches of wehrlite and dunite also occur.

The olivine gabbro of the envelope and enclaves is characterised by an alternation of laminae and medium-thick layers of olivine leucogabbro and olivine gabbro (Fig. 6). Thick layers (1—5 m) of modally laminated olivine leucogabbro are, however, common. Primary structures such as modally-graded and grain-size graded layers are relatively rare in the gabbro, although slump structures and erosional discontinuities are preserved locally.

The gabbro enclaves are intruded by numerous generations of ultramafic and mafic dykes and sheets, many of which contain irregularly distributed xenolithic and xenocrystic fragments of the host rocks. The width of the individual dykes and sheets varies greatly. Some dykes are

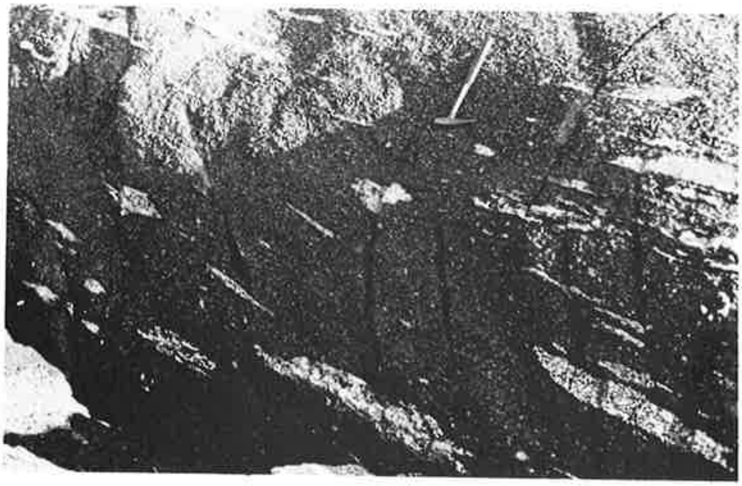

Fig. 7. Olivine melagabbro sheet containing slabs and schlieren of olivine leucogabbro aligned parallel to the fabric in the host olivine gabbro. Melkvann u.c., Steinfjell roof zone.

only a centimetre or so thick while others are several tens of metres wide and can be traced for hundreds of metres. Towards the margins of the larger gabbro enclaves, the proportion of ultramafic dykes and sheets increases, and these areas contain smaller, isolated blocks of gabbro in which the modal layering has an orientation parallel to that in the larger enclaves and in the olivine gabbro envelope. The concordance of the orientation of the layering from one gabbro enclave to the next, regardless of size and distance of separation over large areas requires that substantial parts of the complex developed through protracted emplacement of individual dykes and sheets which gradually fragmented the envelope. A bewildering variety of intrusive phenomena are displayed within and around enclaves. From cross-cutting relationships it has been possible, however, to deduce the following general sequence of intrusive events (Fig. 3):

(1) The passive replacement of olivine gabbro by more mafic and ultramafic rocks to form olivine melagabbro;
(2) The development of irregular olivine clinopyroxenite dykes associated with rheomorphism of olivine gabbro and emplacement of gabbro pegmatite dykes and intrusion breccias;
(3) Emplacement of regular (dilational) ultramafic dykes;
(4) Emplacement of dykes postdating the main evolution of the ultramafic complex.

Passive replacement of gabbro. The initial stages in the development of the ultramafic complex involved the formation within the olivine gabbro of irregular, concordant and subconcordant bodies of olivine melagabbro containing feldspathic schlieren and platy xenoliths of leucogabbro orientated parallel to the fabric in the host (Fig. 7). The distribution of olivine melagabbro is not obviously related to conduits and appears to be the result of replacement of layered olivine gabbro. Some bodies of olivine melagabbro can be traced laterally into xenolithic olivine clinopyroxenite occurring as concordant sheets in the layered gabbro. These commonly contain feldspathic schlieren and tabular xenoliths of leucogabbro preferentially aligned parallel to sheet margins, against which a gradational zone of feldspathic olivine clinopyroxenite is developed in places.

Irregular olivine clinopyroxenite dykes. A later stage of emplacement is represented by discordant ultramafic dykes varying from several centimetres to up to 100 m in width. Traced laterally, such bodies locally display both discordant and concordant relationships with the modal layering in the host olivine gabbro. Discordant contacts typically have an irregular 'saw-tooth' form, and opposite side walls cannot be matched (Fig. 8). The composition and structure of the gabbro along the contacts frequently show considerable modification. Modal plagioclase in the olivine gabbro increases abruptly at the expense of clinopyroxene, forming a troctolitic halo along the contacts. The layering in the gabbro is destroyed during the formation of these haloes. Olivine is usually present in the reaction zones and shows an increase in modal proportion towards the dykes. Internally the

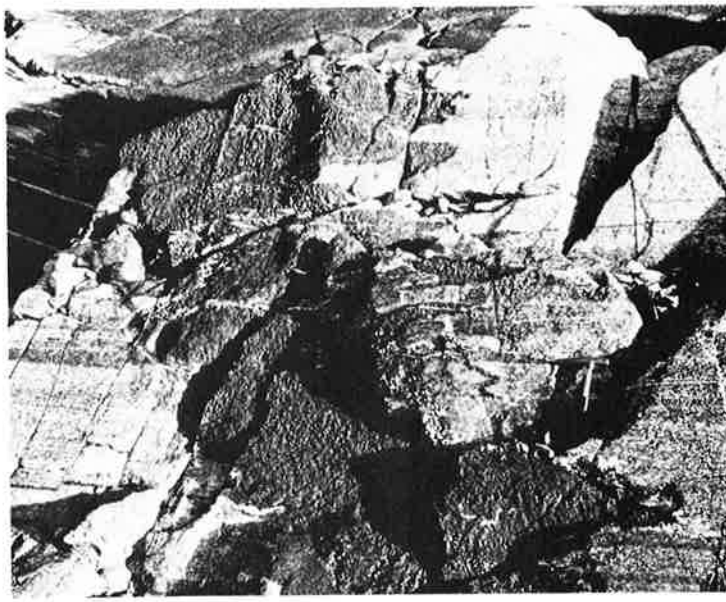

Fig. 8. Irregular olivine clinopyroxenite dyke cutting a modally layered, olivine gabbro enclave. Contacts are lined in places by dunite and show typical 'saw-tooth' form, apparently controlled by compositional variations in the host. Melkvann u.c., Steinfjell roof zone.

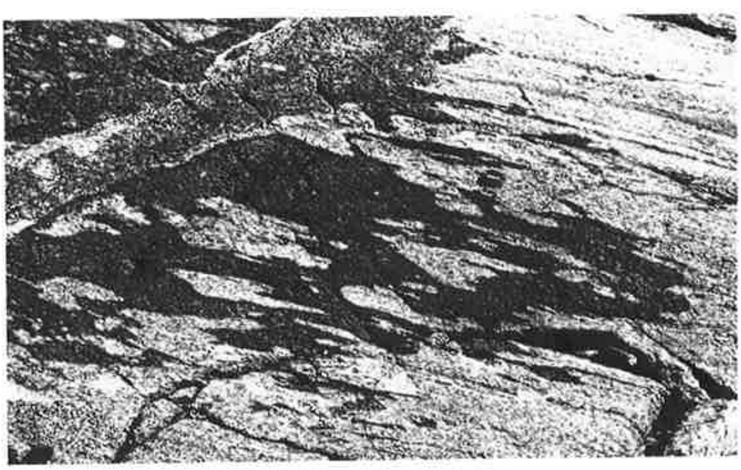

Fig. 9. Higly-irregular margin of an olivine clinopyroxenite dyke. Olivine gabbro enclaves within the dyke contain modal lamination parallel to and are form orientated in concordance with the layered fabric in the host olivine gabbro. Melkvann u.c.

dykes show irregular petrographic variations. Dunite and wehrlite, generally associated with troctolite, are commonly developed adjacent to the irregular contacts, but elsewhere the dyke margins are composed of olivine melagabbro. In contrast, the central parts of the dykes are more homogeneous and consist mainly of olivine clinopyroxenite. The dyke margins, and to a lesser extent the cores, are characterised by small gabbro xenoliths and plagioclase xenocrysts. These are irregularly distributed and a perplexing feature in some dykes is the orientation of elongate gabbro xenoliths at a high angle to the dyke margins such that the layered fabric in the xenoliths is virtually parallel to that in the wall rocks. (Fig. 9). Similarly, zones rich in plagioclase xenocrysts often extend into the dykes from the serrated dyke walls and yet remain parallel to, and appear to represent a continuation of, the layering in the adjacent gabbro. Oblique sections through this type of dyke margin show highly complex contact relationships. Some of the irregular dykes pass into relatively homogeneous concordant sheets of variably feldspathic olivine clinopyroxenite, which in general have sharp regular contacts usually lacking reaction haloes.

The detailed relationships described above,

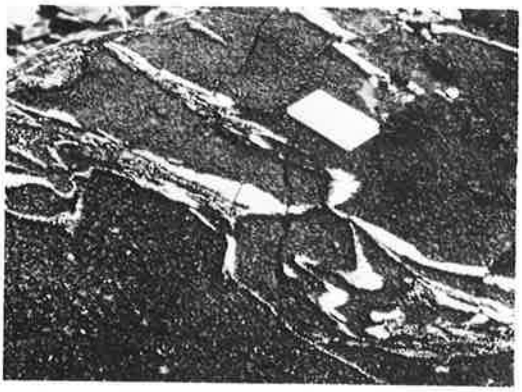

Fig. 10. Anorthositic restites enclosed in variably-feldspathic olivine clinopyroxenite that forms an irregular dyke cutting olivine leucogabbro near Steinfjell, Melkvann u.c. Some restites display disharmonic folds.

in particular the non-matching, irregular dyke walls and the preservation of apparently undisturbed xenoliths within the dykes, indicate that they developed at least in part by replacement of gabbro, through a process involving dissolution, mechanical disaggregation, transport and assimilation by the invading magma as will be discussed later. The structural relationships also suggest that in such dykes, the magma flow must have had a significant lateral component.

The wider dykes of this type (>3 m across) exhibit the contact relationships described above but show a composite internal structure. The central portions of the dykes consist essentially of olivine clinopyroxenite and/or olivine melagabbro containing narrow zones of plagioclase-bearing clinopyroxenite and/or olivine melagabbro which define a crude fluxion banding. These bodies were emplaced by simple dilation within pre-existing, essentially non-dilational dykes. The dilational cores are replete with gabbroic xenoliths in various stages of disaggregation. Elongate xenoliths of anorthosite and leucogabbro, possibly representing restites, characteristically display disharmonic folding (Fig. 10).

Rheomorphism of olivine gabbro; gabbro pegmatite dykes and intrusion breccias

Towards the margins of the larger olivine gabbro enclaves cut by irregular olivine clinopyroxenite dykes, modal layering in the gabbro exhibits various degrees of disruption and reconstitution. Leucogabbro neosomes are developed in the more mafic of the layers and cut across the primary modal layering and ultramafic dykes emplaced into the enclaves (Fig. 11). Discordant, irregular bodies of olivine gabbro pegmatite occur in places, sometimes grading locally into subconcordant anorthositic neosomes. Frequently the gabbro layering becomes highly irregular, mesocratic parts having developed a swirling appearance, while anorthositic layers largely retain their original form. Very locally, the adjacent ultramafic dykes are cut by anorthositic veinlets, while on a much larger scale, dykes of olivine gabbro pegmatite and coeval intrusive breccias invade the ultramafic rocks, forming sub-parallel dyke complexes extending over several kilometres (Fig. 12). Within these dyke complexes, gabbroic and ultramafic dykes display mutually cross-cutting relationships. The olivine gabbro pegmatites typically have comb-textured margins and extremely coarse-grained cores, commonly containing large skeletal olivines up to 10 cm long. The intrusion breccias occur as small plugs and consist of olivine leucogabbro enclosing sub-rounded to angular blocks of various gabbroic and ultramafic rocks (Fig. 13).

Fig. 11. Margin of an olivine gabbro enclave in the Steinfjell roof zone. Olivine clinopyroxenite dykes emplaced into the gabbro are back-veined or disrupted by a leucogabbro neosome. Melkvann u.c.

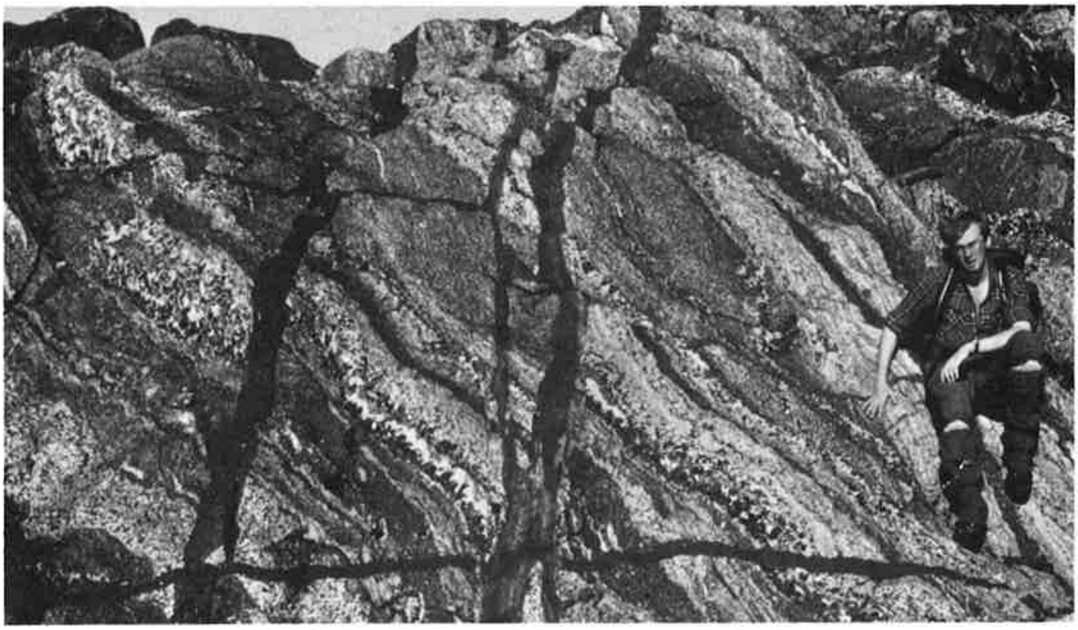

Fig. 12. Inclined subparallel dykes of olivine gabbro and comb-structured olivine gabbro pegmatite emplaced in variably feldpathic olivine clinopyroxenite. The dykes form a NE—SW swarm subparallel to the margin of the Melkvann u.c. to the north of Steinfjell. Two sets of narrow, dilational amphibole-bearing ultramafic dykes post-date the olivine gabbro dykes.

Dilational ultramafic dykes. A further stage in the evolution of the complex is represented by a suite of coarse-grained (>5 mm), dilational ultramafic dykes. These include both simple and composite bodies, and have regular margins often with horns (Robins & Takla 1979), but lack chilled margins. Although represented in the enclave-rich roof zones (Fig. 6), they are most common in the central and eastern parts of the pluton. Cross-cutting relationships within the suite suggest a temporal variation in composition. The earliest dykes are of wehrlite. olivine clinopyroxenite and olivine—hornblende clinopyroxenite, while later dykes characteristically contain abundant primary amphibole with or without plagioclase (both usually occurring as oikocrysts enclosing olivine and clinopyroxene), and have a compositional range from clinopyroxene—hornblende peridotite to olivine—hornblende clinopyroxenite, olivine—clinopyroxenite hornblendite and hornblende melagabbro.

The dykes vary in width from a few centimetres to approximately 20 m, independently of dyke composition. In many areas, especially in the central and eastern parts of the complex, they have a generally east-west orientation, but detailed observation in the Steinfjell area show that the dykes were emplaced along a number of trends: one approximately ENE—WSW, subparallel to the northwestern margin of the complex, one approximately E—W and another

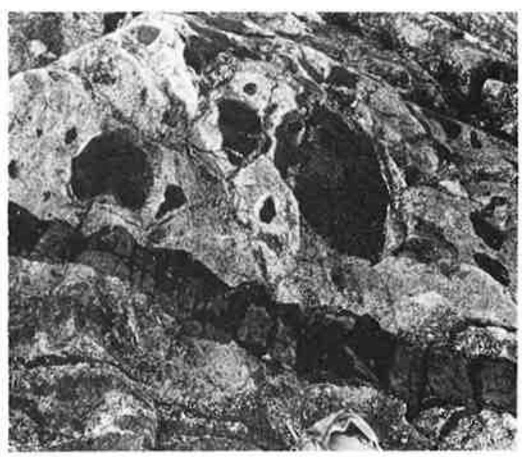

Fig. 13. Intrusion breccia consisting of sub-rounded blocks of ultramafic rocks and olivine gabbro enclosed in olivine leucogabbro. The breccia plug is intruded by an ultrabasic dyke (with chilled margins) belonging to the late-stage, picrite—ankaramite suite. Melkvann u.c., Steinfjell roof zone.

Fig. 14. Olivine—hornblende clinopyroxenite dyke cutting olivine clinopyroxenite. The dyke is choked with angular xenoliths of olivine leucogabbro (foreground and background) and olivine clinopyroxenite (middle ground). Melkvann u.c., Steinfjell roof zone.

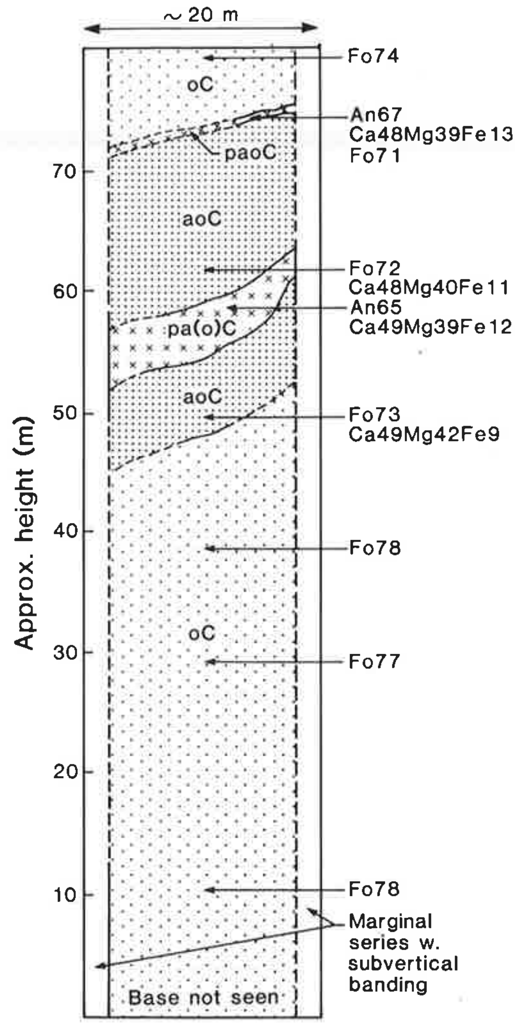

Fig. 15. Simplified vertical section through a layered ultramafic/mafic dyke cutting the margin of the Melkvann u.c. at Steindal, SW of Steinfjell, with mineral compositions as determined by electron microprobe analysis (based on Yeo 1984 and unpublished data). Cumulates within the narrow marginal series are organized in cyclic units involving olivine cumulates (oC), diopside—olivine cumulates (aoC) and plagioclase—salite—olivine cumulates (paoC). The dyke wedges out rapidly above the measured section and its evolution would appear to have involved periodic lateral influxes of magma.

approximately N—S, giving rise to a reticulate dyke pattern.

The latest in the suite are 0.2—1.0 m-wide dilational olivine—hornblende clinopyroxenite dykes, commonly choked with angular xenoliths of their wall rocks (Fig. 14), and which in places occur in swarms providing evidence for local linear extensions of up to 40% (Yeo 1984).

Of particular interest within this suite are dykes showing internal layering, and dykes that contain mantle-derived ultramafic nodules. The layered dykes are of two types. One type contains mineral lamination defined by tabular olivines and oblate oikocrysts of plagioclase and/or amphibole both lying in a plane at a high angle to steeply dipping dyke margins. In the other type, mineral lamination, small-scale modal layering and cyclic repetitions of cumulus assemblages occur (Fig. 15). In the latter, a complete cyclic unit consists of olivine cumulate with post-cumulus plagioclase and clinopyroxene, overlain by clinopyroxene—olivine cumulates and plagioclase—clinopyroxene—olivine cumulates. Amphibole occurs throughout the sequence, but always as a post-cumulus phase, in places forming oikocrysts up to 15 cm across. The modal layering and mineral lamination in these steeply-dipping dykes, which are 15—20 m wide, are parallel and dip at low to moderate angles.

Fig. 16. Spinel lherzolite and subordinate olivine—hornblende clinopyroxenite nodules packing an olivine clinopyroxenite dyke near Holmevann, Melkvann u.c. There is a distinct preferred orientation of xenoliths parallel to the margins of the dyke. Some nodules exhibit compositional banding and some are cut by narrow, plagioclase-bearing olivine—hornblende clinopyroxenite dykes.

Within 1-2 m of the margins there are olivine-rich zones containing a banding parallel to the dyke walls.

The nodule-bearing dykes are generally 5—10 m wide and may be traced over distances of up to 1 km. They are concentrated in a narrow zone trending ENE—WSW from Holmevann to Melkvann (Fig. 2), but similar dykes also occur east and northeast of St. Bekkarfjord and at other localities outside the complex (see Robins 1975, Robins 1982). Those within the complex are, however, contemporaneous with the suite of later ultramafic dykes.

The ultramafic nodules characteristically have low to moderate degrees of roundness and sphericity, many approximating to spindle or plate shapes. The larger nodules measure 40—50 cm across, with a maximum recorded diameter of 60 cm. A preferred orientation of nodules is apparent in some dykes and commonly they are so densely packed that they are in mutual contact, or separated by only thin septa of matrix (Fig. 16). Exposure is generally insufficient for a detailed study of dyke walls, but in some dykes it is clear that the larger nodules are concentrated towards the centre, and nodule diameters decrease towards dyke margins into a zone of dispersed, more rounded nodules, commonly with diffuse margins. The matrix in these dykes is variable in composition, and although locally rich in xenocrystic olivine derived from the break-up of nodules, generally consists of olivine clinopyroxenite with a variable, but usually significant, amphibole content.

The nodule suite consists predominantly of Cr-spinel lherzolites (Carswell 1980), but with a subordinate population (<20%) of olivine—hornblende clinopyroxenites. The lherzolites are mosaic—porphyroclastic varieties (Harte 1977), probably derived from depths no greater than 60 km. Some of the lherzolite nodules contain veins and narrow dykes of plagioclase-bearing olivine—hornblende clinopyroxenite which may well represent pre-inclusion products of partial melting in the upper mantle beneath the ultramafic complex. The suite of olivine—hornblende clinopyroxenites have textures and mineral compositions that are similar to the ultramafic rocks of the Melkvann complex and were probably derived from lower, unexposed levels of the pluton. The dense packing of nodules within the dykes suggests that the nodules accumulated within dyke fissures as the velocity of the entraining magmas decreased (cf. Robins 1975).

Dykes post-dating the complex. Younger intrusive rocks which post-date the formation of the ultramafic complex have a regional distribution and comprise a suite of alkaline olivine basalt affinity dominated by picrite and ankaramite (Robins & Takla 1979) (Fig. 13) and later, more localised pegmatite dykes forming part of the late-D_2 alkaline magmatic activity (Sturt & Ramsay 1965, Robins 1972, 1974, 1980). Within the Melkvann complex, the picrite and ankaramitic dykes represent a number of generations, but all the dykes exhibit chilled margins and the majority have an ENE—WSW trend, following

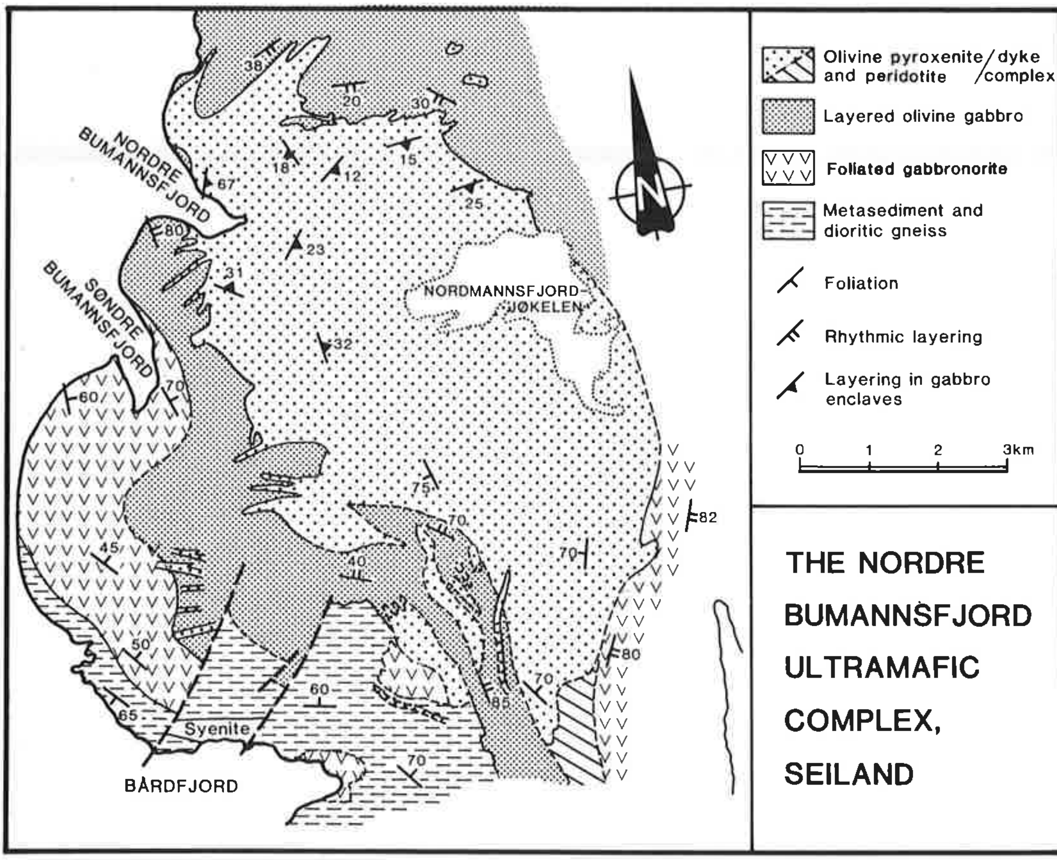

Fig. 17. Simplified geological map of the Nordre Bumannsfjord u.c. and its envelope (based on Sturt et al. 1980, unpublished data from Dr. D.L. Speedyman and the authors' own observations).

a conspicuous set of joints. They must have been emplaced after significant cooling of the complex and were subsequently variably deformed and metamorphosed under lower amphibole facies to upper greenschist facies metamorphic conditions (Ramsay & Sturt 1970, Robins & Takla 1979, Skogen 1980).

The Nordre Bumannsfjord ultramafic complex

The Nordre Bumannsfjord complex, occupies an area of substantial relief in the western part of the island of Seiland (Fig. 1), its outcrop being separated at the head of St. Kufjord from that of the Melkvann complex by a steeply dipping septum of strongly deformed country rocks only 3 km wide. The ultramafic pluton is emplaced mainly into layered olivine gabbro but satellitic ultramafic dykes intrude deformed and metamorphosed gabbronorite along its southwestern margin, and the body terminates southwards in a sheeted complex of ultramafic dykes emplaced in strongly metamorphosed metasediments and dioritic gneiss (Fig 17). To the north and west the strongly discordant contact of the ultramafic complex dips steeply beneath olivine gabbros in which the modal layering dips at low to moderate angles towards the complex. The gabbro envelope appears to have been emplaced into the steep western limb of the major synform developed around the Melkvann mafic—ultramafic complex and has both concordant and highly discordant contacts with an earlier, strongly deformed and metamorphosed (syn-D_1?) subalkaline gabbro and metasediments. The earlier gabbro contains numerous rafts of metasediment (Barth 1961). In the metasedimentary country rocks southwest of the ultramafic complex and its host gabbro

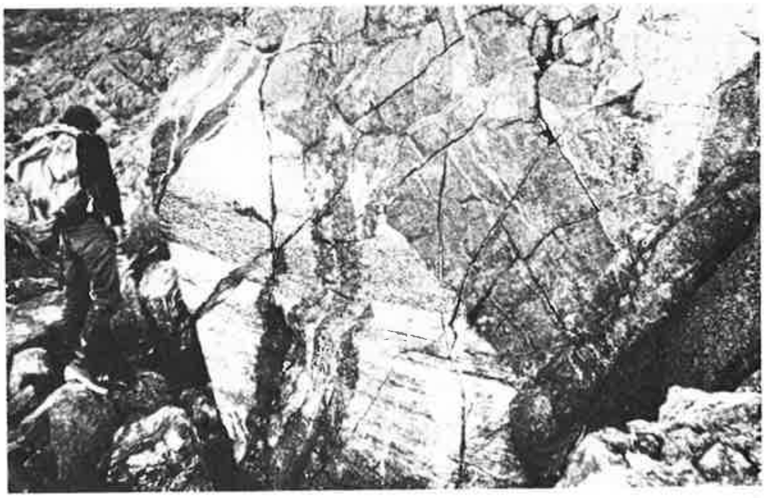

Fig. 18. Modally-layered olivine gabbro enclave intruded by cross-cutting, inhomogeneous ultramafic dykes. N. Bumannsfjord u.c.

a pyroxene—hornfels facies thermal aureole up to 3 km wide is developed in which rheomorphic breccias are common (Sturt et al. 1980). Shear appears to have accompanied contact metamorphism and anatexis of the metasediments.

Marginal dyke swarms. The margins of the ultramafic complex are marked by dense swarms of ultramafic dykes of variable orientation which according to Sturt et al. (1980) have led to the detachment of roof pendants to form large rafts and xenoliths within the complex. Their mapping of the orientation of the modal layering within gabbro enclaves and observations by the present authors suggest, however, that the enclaves have orientations systematically related to the orientation of the layering in the gabbro envelope, even when completely isolated within peridotite (Fig. 17). Ultramafic dykes within the marginal swarms and those cutting gabbro enclaves lack chilled margins and are petrographically diverse and internally inhomogeneous (Fig. 18). Cross-cutting relationships indicate that several generations of dyke emplacement are represented, and although the dykes most commonly consist of variably feldspathic olivine clinopyroxenite, dunite is also represented as well as feldspathic lherzolite, wehrlite, pyrox-

Fig. 19. Margin of olivine clinopyroxenite dyke (right) cutting modally-layered olivine gabbro enclave within the N. Bumannsfjord u.c., east of N. Bumannsfjord. The contact is highly irregular and apophyses extend outwards along the mafic bases of modally-graded layers in the host. Wehrlite is developed in the apophyses and in patches elsewhere along the margins of the dyke.

ene—hornblende peridotite and olivine gabbro, the petrographic range being essentially similar to that within the ultramafic pluton itself. The dykes range in width from several meters to thin veins and commonly display dilational contact relationships. Some of the dykes, however, have irregular saw-tooth contacts which appear to have been controlled by the modal layering of the gabbros they cut or have such highly irregular contacts that an origin by simple dilation would appear to be excluded. Such dykes generally contain narrow, irregular zones of dunite and wehrlite along their walls grading into inhomogeneous olivine clinopyroxenite occupying the main part of the bodies (Fig. 19). Within haloes adjacent to some dykes, clinopyroxene in the gabbro is replaced by olivine which form larger crystals and becomes more abundant towards the dyke contacts. Clinopyroxenite or olivine clinopyroxenite reaction zones a few centimetres wide, grading into olivine gabbro are also present along certain dyke contacts. The dykes generally contain xenoliths and xenocrysts derived from the wall rocks. The xenoliths have both rounded and irregular forms, commonly with ragged margins. In some dykes they are aligned within a crude banding defined by the distribution of xenocrysts derived apparent from the disaggregation of xenoliths (Sturt et al. 1980, Fig. 10a). Some feldspathic pyroxene—hornblende peridotite or hornblende—olivine melagabbro dykes, however, contain distinctly angular, randomly-oriented xenoliths of modally-layered gabbro, olivine clinopyroxenite and wehrlite (Sturt et al. 1980, Fig. 8b). One petrographically distinctive dyke, which can be traced for about 2 km cuts obliquely across the southwestern margin of the complex (Fig. 17). It contains oblate plagioclase and amphibole oikocrysts up to several centimetres across enclosing tabular olivine. The elongation of the oikocrysts is parallel to the lamination defined by the olivine and both dip at a shallow angle between the steep dyke walls. This dyke would appear to be related to the layered dykes present within the Melkvann ultramafic complex.

Remobilization of olivine gabbro. The modal layering of the proximal olivine gabbro host rock and marginal enclaves has locally been modified by the development of patches and veins of leucogabbro within more melanocratic gabbro (Sturt et al. 1980, Fig. 11a). In these places the gabbro may take on a migmatitic appearance, the leucogabbro neosome possessing an ophitic texture and engulfing the layering and tectonic foliation of the host gabbro. Gabbro enclaves within the interior portions of the ultramafic pluton show an increased degree of structural compelxity. Modal layering, primary textures and tectonic foliation are rarely present. The enclaves are strongly recrystallized and have a swirling banding. Olivine gabbro, gabbro and hornblende gabbro pegmatites are widely developed as patches within enclaves or along contacts with ultramafic rocks. Enclaves of migmatitic aspect are closely associated with intrusion breccias of crudely banded leucogabbro enclosing rounded to angular blocks of ultramafic and mafic rocks (Sturt et al. 1980, Figs. 13b, 14b). Intrusion breccias are, however, also developed beside wide satellitic peridotite dykes emplaced in gabbro to the west of the southern part of the ultramafic complex.

Petrographic variations. The coarse-grained ultramafic rocks of the Nordre Bumannsfjord complex are rarely homogeneous and free from inclusions, and a crude interbanding of petrographic types is widely developed. The main rock type is a feldspar-bearing olivine clinopyroxenite which grades in places into wehrlite and dunite, and with an increase in the amount of feldspar, into olivine melagabbro. Pyroxene—hornblende peridotite containing poikilitic amphibole is present locally. Ultramafic rocks carrying xenoliths of gabbronorite or metasediment are generally feldspar-bearing lherzolite or spinel lherzolite, respectively. Around metasedimentary xenoliths harzburgite is developed. In a number of places, and in particular along the eastern margin of the complex, the ultramafite possess a penetrative tectonic foliation and have been recrystallized at high temperatures. Throughout most of the complex, deformation is restricted to widely spaced shear zones and the development of a fracture cleavage.

Late mafic and ultramafic dykes. The ultramafic complex was cut at a lage stage in its development by a variety of pegmatitic veins and dykes of which only some of the youngest have chilled margins. The veins, which commonly show comb structure, frequently form the margins of composite dykes cored by either medium-grained gabbroic rocks (Sturt et al. 1980, Fig. 13a) or coarse-grained ultramafic rocks. Vein compositions of olivine gabbro, olivine gabbronorite, gabbronorite and hornblende gabbro have been recorded. Pegmatites occurring as parallel-sided veins cutting ultramafics have been observed to pass laterally into zones where they become flow-folded. Other veins are deformed and foliated but are cut by later undeformed veins. The late dykes in the complex are petrographically diverse and include wehrlite, felspathic pyroxene—hornblende peridotite, gabbro, hornblende gabbro and blastoporphyritic amphibolite (picrite and ankaramite). According to Sturt et al. (1980), the dykes extend outwards into the envelope but are concentrated within the pluton. The magmatic activity responsible for the dykes would appear to represent a late stage in the evolution of the complex, since late phases include wehrlite and other ultramafic rocks, but a comprehensive sequence of dyke emplacement has not been etablished. The dykes have a preferred NW—SE orientation and in places occur as dense swarms associated with linear extensions of up to 40% (Sturt et al. 1980, Fig. 13 & Table 2). Towards the central parts of the pluton, however, the dykes assume a more random orientation and some are included as blocks in intrusion breccias.

The Kvalfjord ultramafic rocks

Ultramafic rocks on the eastern part of the island of Stjernøy (Fig. 1) apparently occur in two steep-sided and virtually coalescent intrusive centres emplaced in tectonized, modally-layered olivine gabbro (Fig. 20). On a large scale the contacts of the ultramafic body are clearly intrusive, cutting discordantly through the layering of the host gabbro. Enclaves of gabbro up to several hundreds of metres across are included within the ultramafic rocks (Fig. 21) and sheets and dykes of wehrlite, peridotite and feldspathic olivine—hornblende clinopyroxenite are common in the gabbro along the contacts of the body.

The envelope. The olivine gabbro of the envelope is emplaced into quartzo-feldspathic paragneiss, a broad zone of rheomorphic breccias being developed along the intrusive contact. The modal layering of the olivine gabbro, and the tectonic foliation which is generally parallel to it, are deformed by a synform plunging generally southwards, but the ultramafic pluton cuts through the hinge of this structure. The northern limb of the synform is dissected by a series of westward-dipping thrusts (Fig. 20) which bring the olivine gabbro above a thin thrust sheet of strongly deformed metagabbro, monzodiorite and perthosite which in turn is thrust over carbonatite and fenites (Robins & Tysseland 1983). The ultramafic rocks occurring around the head of Store Kjerringfjord appear also to rest on a thrust plane, and may form a thrust wedge sandwiched between slices of olivine gabbro. Despite these local tectonic complications the gabbroic cumulates can be seen to form a layered sequence at least 4 km and possibly as much as 8 km thick. Cumulate structures are preserved only locally, having been overprinted and highly modified by penetrative high-temperature deformation and recrystallization. Modally-graded layers showing a consistent way-up pattern have not been observed, and a systematic cryptic layering has yet to be detected. Oosterom (1963) reported large-scale alternations of modally-layered olivine gabbro with leucogabbro and anorthosite, the latter locally forming discrete units up to 10—20 m thick. In some areas the primary layering is highly disturbed and irregular in orientation, folded intensely by flow folds or affected by autobrecciation. Adjacent to uncomplicated contacts with the ultramafic complex the olivine gabbro is granoblastic and exhibits modal layering modified by recrystallization. To the southwest of the ultramafic complex the olivine gabbros are intruded by a considerable volume of coarse-grained to pegmatitic rocks varying from hornblendite to hornblende gabbro. Contacts of the amphibole-rich rocks are sharp and discordant, and the surrounding gabbros are cut, and in places brecciated by networks of amphibole-rich dykes or veins.

Olivine clinopyroxenite and related rocks. The main rock type in the ultramafic complex is a coarse-grained and relatively homogeneous olivine clinopyroxenite locally varying to wehrlite, clinopyroxenite, inhomogeneous amphibole- and plagioclase-bearing olivine clinopyroxenite and olivine melagabbro. The olivine clinopyroxenite contains sporadic angular to rounded, coarse-grained xenoliths of wehrlite (Fig. 22) and dunite. The ultramafic rocks are generally separated from the olivine gabbro of the envelope by a sheeted zone up to 1 km wide (Fig. 20) in which olivine melagabbro, plagioclase-bearing olivine—hornblende clinopyroxenite and wehrlite are interleaved with olivine gabbro (the olivine melagabbro zone of Oosterom, 1963). The foliation present in the gabbro enve-

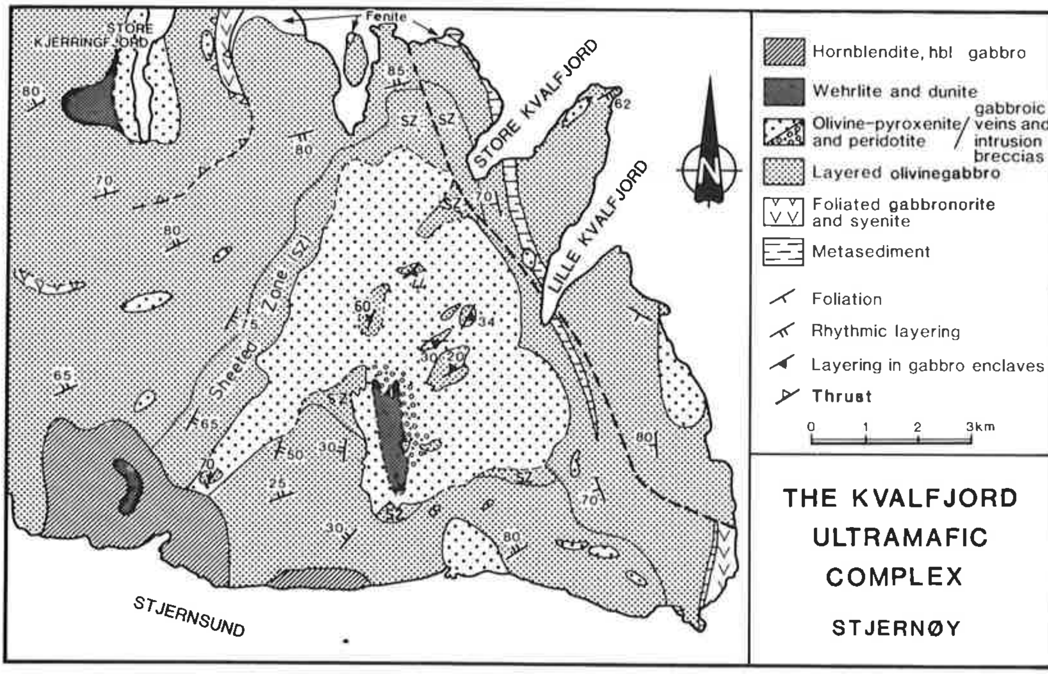

Fig. 20. Simplified geological map of the Kvalfjord ultramafic complex and its envelope (based on Oosterom 1963, Robins & Tysseland 1963 and the authors' own observations).

lope is not apparent in the olivine clinopyroxenite. In the vicinity of contacts with the host rocks and olivine gabbro enclaves, however, the ultramafic rocks generally have a streaky and impersistent banding defined by the distribution of plagioclase xenocrysts and the crude alignment of concentrations of olivine and pyroxene. Olivine clinopyroxenite dykes within gabbro enclaves are commonly xenolithic, and the irregular contacts with olivine gabbro, olivine leucogabbro or troctolite xenoliths and the wall rocks may be marked in some cases by narrow zones of dunite or poikilitic wehrlite. Olivine-poor gabbro towards discordant contacts with olivine clinopyroxenite commonly contains increasing amounts of large, irregular olivine crystals. Concordant xenolithic olivine clinopyroxenite intrusions in olivine gabbro can in some places be traced laterally into olivine melagabbro in which much of the plagioclase present appears to be related to aligned olivine gabbro xenoliths and may be interpreted as xenocrystic.

Wehrlite. In the southern part of the ultramafic complex olivine clinopyroxenite and olivine gabbro enclaves are invaded by a fairly extensive body of banded wehrlite (Fig. 20). The wehrlite contains small, elongate and parallel-orientated inclusions of olivine-rich wehrlite, olivine gabbro, olivine clinopyroxenite and pegmatitic clinopyroxenite, all possessing highly irregular margins; the wehrlite itself grades into bands of olivine clinopyroxenite and olivine melagabbro. Where enclaves of olivine gabbro are associated with the wehrlite these are cut by wehrlite dykes but the gabbro has a nebulous and irregular banding and appears in places to have back-veined the wehrlite dykes. The northern and eastern margins of the wehrlite are marked by a zone of intrusion breccias (Fig. 23) in which a matrix of olivine gabbro or melagabbro carries both rounded and angular blocks of olivine gabbro, some of which exhibit modal layering, as well as ultramafic rocks varying in composition from wehrlite to olivine clinopyroxenite.

Poikilitic wehrlite (locally feldspathic and often with patches of dunite and coarse-grained to pegmatitic olivine clinopyroxenite and clinopyroxenite) also forms tabular or irregular dykes a few centimetres to several metres in width traversing both olivine clinopyroxenite and olivine gabbro enclaves. Contacts of the wehrlite

Fig. 21. Margin of large, olivine gabbro enclave cut by several generations of ultramafic dykes. Modal layering in the enclave is disturbed by flow folds. Kvalfjord u.c., between Lille and Store Kvalfjord.

dykes with olivine clinopyroxenite show no sign of chilling and vary from sharp to gradational. Narrow marginal zones of dunite are developed in some instances while other dykes grade into marginal zones of olivine clinopyroxenite. Pods and irregular patches of coarse-grained to pegmatitic olivine clinopyroxenite and clinopyroxenite are commonly present along dyke margins and are often crudely aligned with the contacts. Wehrlite dykes emplaced in olivine gabbro enclaves typically contain irregular, slabby to rounded xenoliths of olivine gabbro. Xenoliths are frequently aligned parallel to the general trend of dyke margins but these may be highly irregular in detail. Coarse-grained dunite is locally found along contacts of the wehrlite dykes with the gabbro host as well as around the margins of xenoliths. Dunite, wehrlite and troctolite are developed in irregular patches and lenses extending along the relict modal layering of the host olivine gabbros adjacent to some wehrlite dykes (Fig. 24). Some steeply-dipping wehrlite dykes contain a more or less pronounced olivine lamination orientated at angles up to 90° to their contacts; strong mineral lamination has been noted in dykes as narrow as 20 cm.

In the northeastern part of the ultramafic complex poikilitic wehrlite together with subsidiary olivine-rich olivine clinopyroxenite and dunite commonly form irregular veins and bodies a few centimetres to several metres across within olivine clinopyroxenite (Fig. 25). The complicated form of these bodies appears to preclude emplacement by dilation, and they are believed to have developed by replacement.

Late dykes and veins. The Kvalfjord complex is intruded by several generations of coarse-grained to pegmatitic olivine gabbro veins lacking chilled margins and which in places form dense swarms (Fig. 26). The veins occur both as simple bodies from a few centimetres to some metres wide, generally exhibiting a comb structure and sometimes containing skeletal olivine, and as the marginal zones of composite dykes, the cores of which may be occupied by olivine—hornblende clinopyroxenite or wehrlite. Olivine—hornblende clinopyroxenite as well as oliv-

Fig. 22. Rounded xenoliths of coarse-grained wehrlite within olivine clinopyroxenite. Lille Kvalfjord valley, Kvalfjord u.c.

Fig. 23. Intrusion breccia containing angular blocks of olivine clinopyroxenite within a matrix of olivine gabbro. Kvalfjord u.c., Lille Kvalfjord valley.

ine gabbro, hornblende gabbro and olivine leucogabbro dykes of dilational form also occur in the ultramafic complex. These minor intrusions characteristically lack chilled margins and while they cross-cut some ultramafic rocks they are themselves cut by subsequent ultramafic dykes. A suite of dilational, variably foliated and amphibolitized olivine gabbro dykes preserving chilled margins represents one of the latest magmatic events within the complex. These dykes are post-dated only by nepheline syenite pegmatites which are widely developed within the complex and its envelope.

The Reinfjord ultramafic complex

The Reinfjord complex (Fig. 1) lies some 50 km souhwest of Seiland and Stjernøy and although of comparable (syn-D_2) age differs from the other high-temperature ultramafic complexes in two important respects. Firstly, the Reinfjord complex contains extensively developed layering together with a crudely concentric modal and cryptic variation. Secondly, it is emplaced into a layered gabbro of subalkaline character (the Langstrand gabbronorite), and to some extent this is shared by the ultramafic cumulates themselves.

Recent re-investigation of the Reinfjord Complex has led to a revision of the nomenclature originally proposed (Bennett 1974) for the various parts of the complex. The subdivision adopted here (Table 2) conforms more closely to the terminology for layered intrusions proposed by Irvine (1982).

The exposed part of the Reinfjord ultramafic complex contains two early layered series, one structurally above the other and separated by a sub-concordant screen of gabbro that projects from the envelope into the southwestern corner of the complex (Figs. 27 & 28). The Lower Layered Series, consisting mainly of lherzolite, wehrlite and olivine clinopyroxenite, is restricted to a level below the gabbro screen and is exposed only in the southwestern corner of the complex. The Upper Layered Series, consisting of wehrlite and olivine clinopyroxenite, has a more extensive outcrop above the gabbro screen, and forms a plateau 550—800 m a.s.l. Both laye-

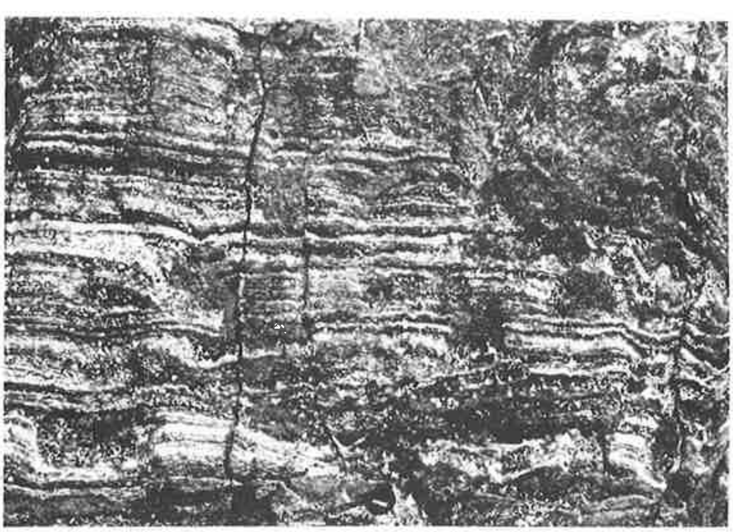

Fig. 24. Relict modal layering within an olivine gabbro enclave partially replaced by troctolite, wehrlite and dunite. Kvalfjord u.c.

Fig. 25. Veins and patches of secondary wehrlite and dunite developed within massive olivine clinopyroxenite. Kvalfjord u.c.

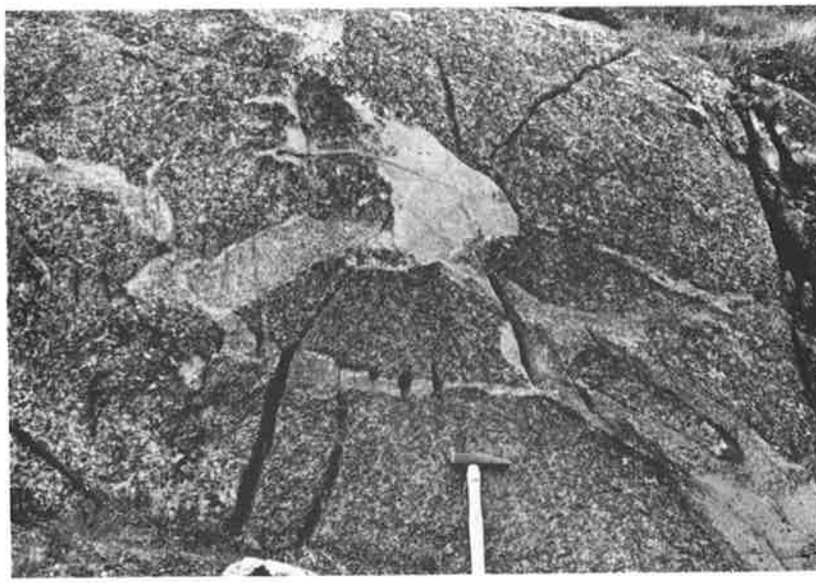

Fig. 26. Swarm of pegmatitic olivine gabbro veins cutting peridotite and commonly forming the margins of composite dykes. Kvalfjord u.c.

red series pass laterally through transitions of variable width into marginal zones dominated by websterite and olivine websterite but also containing smaller volumes of olivine melagabbro and troctolite, spatially associated with numerous gabbroic xenoliths in various stages of assimilation, and blocks of coarse-grained pyroxenite.

In the central part of the complex, an extensive outcrop of dunite and subsidiary poikilitic wehrlite represents a later phase of intrusion. Towards the eastern and western margins of the complex, this later body is grossly discordant and cuts both the Upper Layered Series and its time-equivalent Upper Marginal Zone. Towards the south, it extends as a relatively narrow

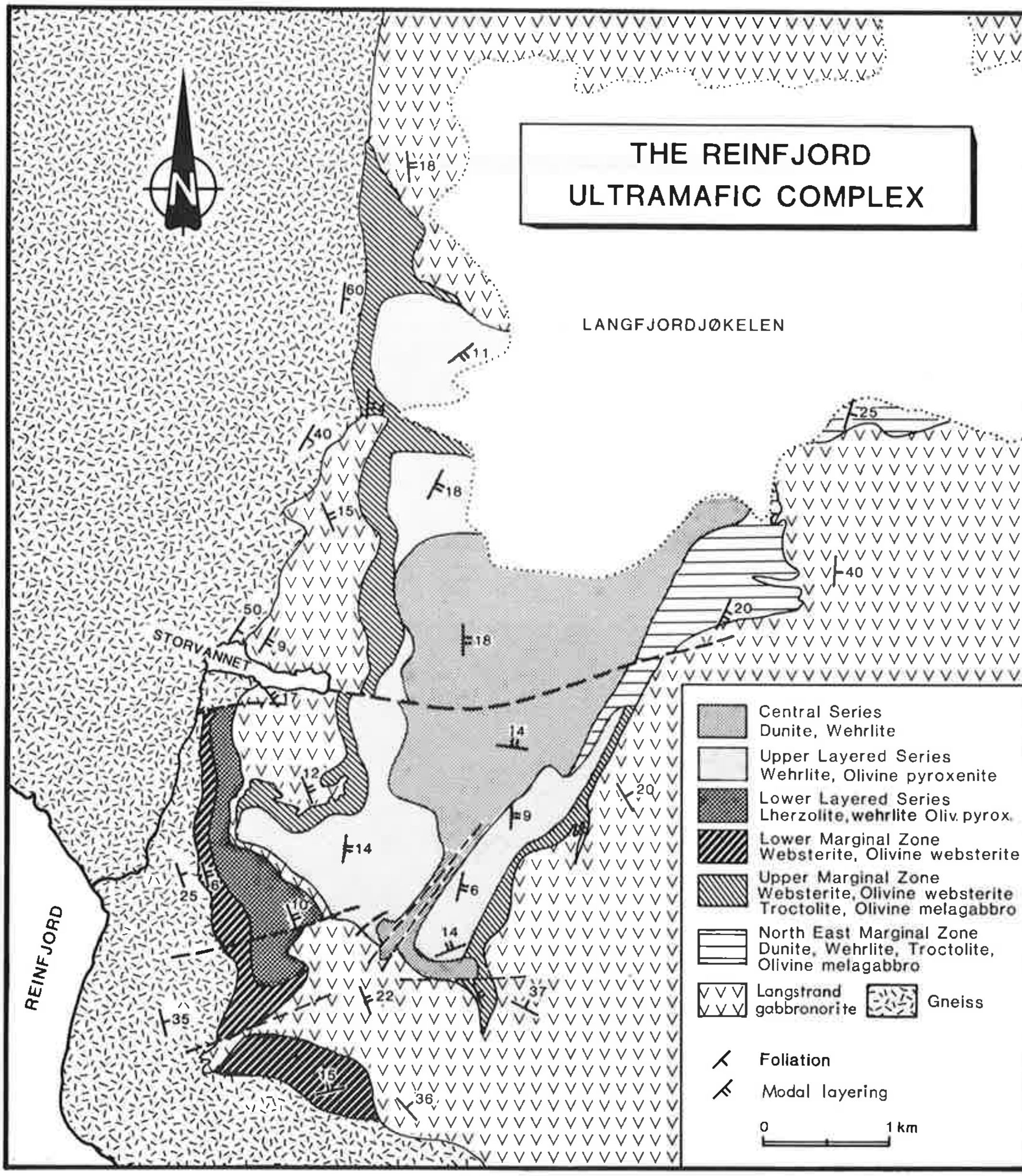

Fig. 27. Simplified geological map of the Reinfjord ultramafic complex and its envelope. See Table 2 for the subdivision of the complex.

tongue to the southern margin of the complex, forming a steep-sided, dyke-like body, 100—200 m wide.

Extrapolation of outcrop data suggests that the Reinfjord complex approximates to a crudely elliptical cylindroid plunging very steeply in a northeasterly direction. Contacts with its envelope are strongly discordant, being either near vertical or steeply inclined to the northeast or east. Locally, however, contacts are irregular in detail and are to varying degrees influenced by the gently or moderately inclined modal layering in the gabbro envelope along which there are sill-like projections. This type of con-

Fig. 28. Panorama of the southwestern corner of the Reinfjord u.c. Gneisses of the envelope form the bluffs below the extensive screes. The Lower Layered Series can be seen in the lower part of the cliff and is separated from the Upper Layered Series by the light-coloured gabbro screen. Alternations of sequences of olivine and clinopyroxene—olivine cumulates and large, lensoid gabbro rafts are visible in the layered series.

tact is particularly well developed adjacent to the gabbro screen between the Lower and Upper Layered Series where subconcordant ultramafic sheets are separated by leucogabbro (Fig. 29). Ultramafic dykes cutting the gabbro emvelope occur locally, but compared with the ultramafic complexes of Seiland and Stjernøy are relatively uncommon, and rarely extend more than 50 metres from the main pluton.

The envelope. The Reinfjord complex is almost entirely confined to the western part of the syn-D_2 Langstrand gabbronorite. Along the southwestern margin of the complex, the Lower Marginal Zone is shown in Fig. 27 to be in contact with metasediment. A 1—3 m thick screen of recrystallised and rheomorphic gabbro is, however, preserved in a number of places along this contact, suggesting that here the margin of the ultramafic complex more or less coincides with the margin of the earlier gabbro. In the vicinity of Storvannet, the Upper Marginal Zone lies well within the gabbro envelope, but farther north, 1 km west of Langfjordjøkelen, ultramafic rocks are in direct contact with metasediments.

The Langstrand gabbronorite is a steep-sided layered pluton (Hooper 1971, Bennett 1971, 1972) emplaced into psammitic and semipelitic paragneiss, the Garnet Gneiss Group of Hooper & Gronow (1969). The lowermost cumulates of the pluton are exposed on the western side of the ultramafic complex, at Storvannet (Fig. 27). Here the most westerly outcrops of gabbro constitute a banded marginal series, some 20 m wide and steeply inclined to the east. This passes laterally into a sequence of plagioclase—clinopyroxene—olivine cumulates in which olivine has the composition Fo_{77-75} and plagioclase An_{70-60} (Bennett 1972, Emblin 1985). The higher parts of the layered sequence, exposed to the north, south and east of the ultramafic complex contain numerous concordant metasedimentary rafts and consist mainly of leucocratic gabbronorite containing hypersthene (An_{71-63})and plagioclase in the range An_{57-48}. Olivine is present, however, in the gabbronorite within zones several metres wide along contacts with the ultramafic complex.

The paragneiss, cropping out in a post-D_2 antiform to the west of the Langstrand gabbronorite was earlier believed to represent the oldest part of an Eocambrian (Vendian) cover

Fig. 29. The subhorizontal upper contact of the gabbro screen with the Upper Marginal Zone of the Reinfjord u.c. Thin screens of recrystallized leucogabbro are separated by modally-layered variably felspathic olivine websterite and lherzolite.

sequence (Hooper & Gronow 1969, Hooper (1971), but more recent studies elsewhere in the Seiland province (Akselsen 1980, Ramsay et al. 1985) suggest that it is probably of Precambrian age, and forms the basal plinth of the Sørøy Nappe.

Due west of Langfjordjøkelen, where the ultramafic complex is directly in contact with metasediment, partial melting has produced a 20—30 m-wide zone of rheomorphic breccias with granitic and granodioritic neosomes. A thermal aureole developed in the metasediments extends up to 2 km from the western intrusive contact and is characterised by sillimanite and K-feldspar (Bennett 1974). Replacement of sillimanite by kyanite in the outer parts of the aureole suggests that crystallisation and cooling of the ultramafic complex occurred under confining pressures of at least 6 kbar (Althaus 1967, Richardson et al. 1969). Within the marginal zones of the ultramafic complex, coronas along olivine—plagioclase grain boundaries provide corrobortive evidence for subsolidus cooling at confining pressures of 6—8 kbar (Kushiro & Yoder 1966, Ito & Kennedy 1971), corresponding to crustal depths of 22—28 km within the orogenic belt. Recently obtained analyses (Lord & Bennett, unpublished data) of coexisting cordierite (Fe/Fe+Mg = 0.39), almandine garnet (Fe/Fe+Mg = 0.73) and plagioclase from a pelitic raft within the Langstrand gabbronorite, close to the southern margin of the Reinfjord complex, suggest that peak metamorphic conditions, corresponding with the emplacement of the gabbronorite, were c. 875°C and c. 7.5 kbar (Aranovich & Podlesski 1983, Ghent 1979) assuming $P_{H_2O} = P_{Total}$

The Layered and Central Series. Field relations, modal and cryptic variations require that three major phases of intrusion are represented by the Lower and Upper Layered Series and the Central Series of the Reinfjord complex. The Lower and Upper Layered Series contain sequences of olivine and modally-layered clinopyroxene—olivine cumulates, while the Central Series contains only olivine cumulates.

The Lower Layered Series represents the earliest phase of intrusion and comprises four cyclic units, each composed of olivine cumulates followed by clinopyroxene—olivine cumulates, in a 300 m-high section exposed in the southwestern part of the complex (Fig. 28). The olivine cumulates are lherzolites containing large bronzite oikocrysts, and poikilitic wehrlites. The clinopyroxene—olivine cumulates are lherzolites with oikocrystic bronzite, wehrlites and olivine clinopyroxenites (Fig. 30).

The Upper Layered Series represents the second major phase of intrusion. Seven cyclic units, each consisting of olivine cumulates followed by clinopyroxene—olivine cumulates, have been recognised within the 250 m-thick sequence preserved. The olivine cumulates are poikilitic spinel wehrlites and the clinopyroxene—olivine cumulates are wehrlites and olivine clinopyroxenites. In the lower cyclic units olivine cumulates dominate, whereas clinopyroxene—olivine cumulates predominate in the higher units.

Vertical cryptic variation within the sequences of cyclic units is extremely limited. Recent work has established a total vertical variation of olivine composition within the Lower Layered Series of Fo_{83-80} and within the Upper Layered

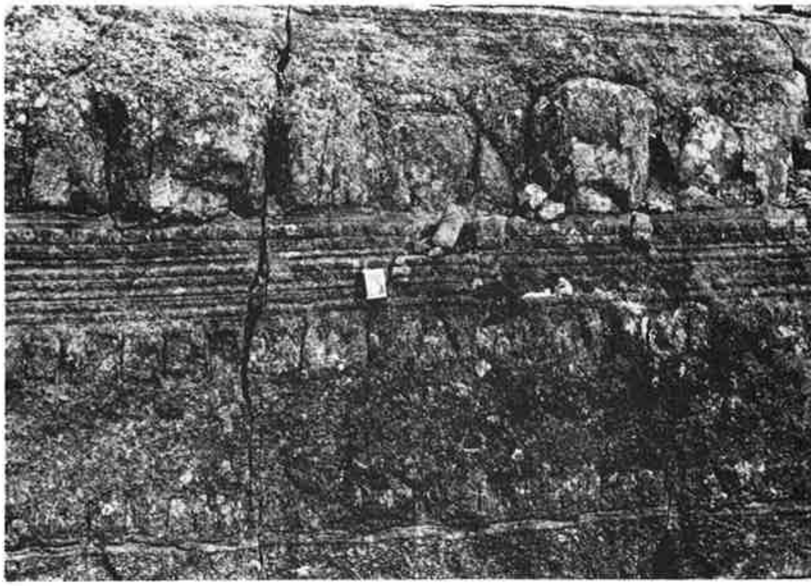

Fig. 30. Cm- and dm-scale modal layering in clinopyroxene—olivine cumulates from the Lower Layered Series of the Reinfjord u.c.

Series of Fo_{85} — Fo_{81}. The Upper Layered Series appears also to show a slight lateral cryptic variation amounting to c. 2 mole % forsterite over a distance of 500 m. This series contains large blocks of massive websterite (Fig. 31) and either massive or crudely layered olivine websterite, sometimes including gabbro xenoliths. Beneath such blocks, which appear to be concentrated at a particular stratigraphic horizon, the modal layering is disrupted and folded, while the overlying layers drape over the blocks. These relationships indicate that the blocks are autoliths and were probably derived from the Upper Marginal Zone.

The discordant Central Series represents a third major phase of intrusion and crystallization, during which olivine was the only cumulus phase. The series consists mainly of dunite and subordinate poikilitic wehrlite, and exhibits a range in olivine composition from Fo_{86} to Fo_{84} However, within the sequence of olivine cumulates there appears to be a regression in

Table 2. Subdivision of the Reinfjord ultramafic complex. Olivine compositions by electron microprobe analysis (Emblin 1985)

SERIES	ROCK TYPES	ASSOCIATED MARGINAL ZONES	ROCK TYPES
CENTRAL SERIES	OLIVINE CUMULATES Dunite, wehrlite $Fo_{83.6}$—$Fo_{85.9}$	NORTHEAST MARGINAL ZONE	Dunite, wehrlite, olivine websterite, websterite, troctolite, olivine melagabbro $Fo_{78.1}$—$Fo_{83.5}$
UPPER LAYERED SERIES	OLIVINE AND CLINO-PYROXENE—OLIVINE CUMULATES wehrlite, olivine clinopyroxenite $Fo_{81.0}$—$Fo_{85.3}$	UPPER MARGINAL ZONE	Olivine websterite, websterite, olivine gabbro $Fo_{74.0}$—$Fo_{80.9}$
LOWER LAYERED SERIES	OLIVINE AND CLINO-PYROXENE—OLIVINE CUMULATES lherzolite, wehrlite, olivine clinopyroxenite $Fo_{79.9}$—$Fo_{82.9}$	LOWER MARGINAL ZONE	Olivine websterite, websterite, olivine melagabbro $Fo_{76.7}$—$Fo_{81.6}$.

Fig. 31. Lensoid block of massive, coarse-grained websterite, probably derived from the Upper Marginal Zone, enclosed within modally-layered olivine—clinopyroxene cumulates of the Upper Layered Series. Reinfjord u.c., west of Storvannet.

Mg/Mg+Fe ratio, suggesting that more than one pulse of magma was responsible for the Central Series.

The contacts between the Central Series and older ultramafic cumulates, although discordant and intrusive in a general sense, are generally highly irregular and display evidence of metasomatic activity, in which pyroxene was replaced by secondary olivine. Numerous examples exist of the partial replacement of clinopyroxene-rich layers within the Upper Layered Series by olivine, without disruption of the layering, and where irregular bodies and veins of dunite cut across but do not disrupt the modal layering (Fig. 32). Less commonly, non-dilational dykes of dunite cut the cumulates of the Upper Layered Series. These features are restricted to the vicinity of the contact of the Central Series and are clearly related to its emplacement. They give evidence of reaction between fluids derived from the Central Series and pyroxenes of the Upper Layered Series.

The narrow extension of the Central Series southwestwards through the Upper Layered Series (Fig. 27) consists mainly of poikilitic wehrlite. Although this body is essentially a dyke, numerous thin sheets of poikilitic wehrlite project laterally from the dyke into the Upper Layered Series. Many of these sheets have irregular contacts,and enclose partially disrupted aggregates of pyroxene, presumably derived from the host rocks. The structures at the base of one of the wehrlite sheets suggest that the dyke-like extension of the Central Series was emplaced into variably consolidated earlier cumulates.

The Marginal Zones. Marginal zones, comprising pyroxene-rich ultramafic rocks characterised by variable contents of orthopyroxene and/-or plagioclase and containing gabbroic wall-rock xenoliths, are lateral time equivalents of the various layered series. The Lower Marginal Zone is developed adjacent to the Lower Layered Series, the Upper Marginal Zone adjacent to the Upper Layered Series, and the Northeast Marginal Zone adjacent to the Central Series where it intrudes the Upper Marginal Zone and the gabbro envelope, to the southeast of Langfjordjøkelen (Fig. 27 and Table 2).

Unlike the marginal series of many layered intrusions, the Lower and Upper Marginal Zones within the Reinfjord complex lack any modal layering or banding orientated roughly parallel to contacts. Instead, both these marginal zones contain various types of macrofabrics that are laterally continuous with the modal layering in the adjacent layered series.

The Lower Marginal Zone consists of a transitional sequence of thick (>1 m) gently-dipping layers of olivine websterite containing large bronzite oikocrysts and an outer part of apparently massive websterite and olivine websterite. The massive rocks in places contain numerous small (cm scale) corroded xenoliths of metasedimentary origin. Within the thickly-layered units, lensoid xenoliths of gabbro mantled by coarse-grained websterite lie with their long axes within the plane of the layering. Olivines within the Lower Marginal Zone are significantly more Fe-rich than in the Lower Layered Series, and lie in the range Fo_{82} — Fo_{77}.

Fig. 32. Replacement of clinopyroxene by olivine in the Upper Layered Series of the Reinfjord u.c. is common close to the discordant contact with the Central series. Irregular bodies and fingers of wehrlite and dunite transgress, but do not disrupt, the modal lamination in the earlier clinopyroxene—olivine cumulates.

The Upper Marginal Zone is developed between the Upper Layered Series and the envelope, which except in the extreme northwest, consists of the Langstrand gabbronorite. The lithologies developed are similar to those in the Lower Marginal Zone, but also include abundant olivine melagabbro and troctolite associated with gabbroic xenoliths. Although not shown in Fig. 27 for reasons of clarity, the Upper Marginal Zone extends along the top of the gabbro screen. Here the modal proportion of plagioclase in the zone decreases upwards. Adjacent to the rheomorphic breccias due west of Langfjordjøkelen, the Upper Marginal Zone is dominated by massive websterite, but with macropoikilitic olivine melagabbro developed in places, particularly within 5 metres of the contact. This part of the zone contains higher modal pyroxene and plagioclase and lower modal olivine than elsewhere. The range of olivine compositions measured in the zone as a whole lies between Fo_{81} and Fo_{74}.

The Northeast Marginal Zone contains xenoliths and hybrids resulting from intrusion of Central Series into the Upper Layered Series, its associated marginal rocks, and the gabbro envelope along the eastern margin of the complex (Fig. 27). Lithologies in this zone include dunite and poikilitic wehrlite, in addition to olivine websterite, olivine melagabbro and troctolite. Associated with these are gabbro xenoliths, some of which form large (> 10 m long) lensoid slabs.

The presence of gabbro xenoliths is a feature common to all three marginal zones, but gabbro xenoliths also occur within the Lower and Upper Layered Series close to the marginal zones. The xenoliths occur in various stages of assimilation, and vary in size from large recrystallized gabbro slabs, up to 200 m long in section, to small leucogabbro restites a few centimetres across. Most xenoliths are surrounded by a coarse pyroxenite reaction rim, the outer margin of which sometimes contains olivine.

Ultramafic and mafic dykes. Relatively narrow (<15 cm wide) ultramafic and mafic dykes are common within the layered series, but are particularly abundant within the main outcrop of the Central Series (Fig. 33). Dyke compositions vary from dunite, through wehrlite and lherzolite to pyroxenite, olivine melagabbro and gabbro. Crosscutting relationships at individual stations indicate a complex sequence of emplacement. Most dykes are dilational, but some are replacive. Bennett (1974) suggested that the earlier dykes were produced by remobilisation of intercumulus liquids, and the later gabbroic dykes were derived from residual melts. This simple interpretation will undoubtedly be revised in the light of further investigation.

Deformation within the complex. Most rocks within the complex show variable degrees of high-temperature recrystallization. While this tends to obscure primary cumulus textures at the microscopic scale, mesoscopic and macroscopic features are extremely well preserved. A late-D_2 high-temperature foliation, sometimes containing macropoikilitic schlieren of pyroxene and/or plagioclase, is present in parts of the

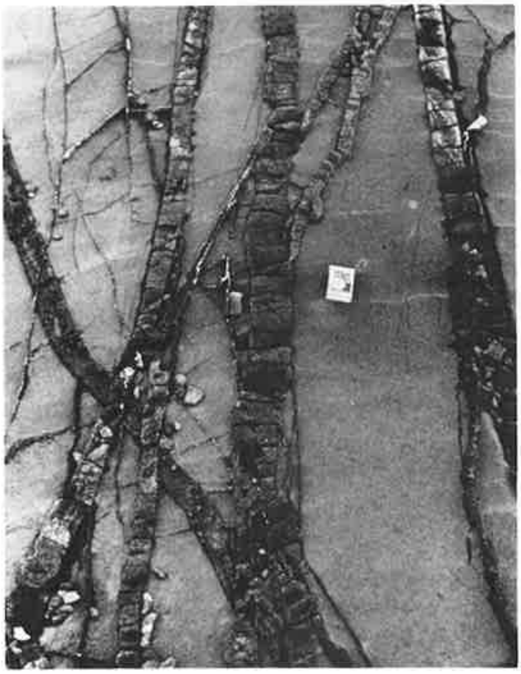

Fig. 33. Narrow, cross-cutting, dilational, mafic and ultramafic dykes emplaced into massive olivine cumulate of the Central Series of the Reinfjord u.c.

complex close to contacts with the gabbro envelope, and dips at 25°—40° in a northeasterly direction (Bennett 1974). Later, post-emplacement ductile deformation is mainly restricted to discrete shear zones whilst later brittle deformation is represented by a number of NE—SW-trending faults which are displaced by E—W trending fault zones. One of the latter cuts the complex east of Storvannet, and has provided a pathway for the aqueous fluids responsible for the high degree of serpentinization present along this lineament.

Summary

The preceding descriptions show that while each of the ultramafic complexes of northern Norway has a structural and petrographic individuality, there are a number of common features. The latter must form the basis of any synthesis of the genesis of the ultramafic rocks. In this section the phenomena common to all of the complexes and their distinctive features are summarized and discussed.

The intrusive sequences

Although the intrusive sequences represented within the complexes differ in detail there appears to be a general trend towards emplacement of more olivine-rich rocks with time. This is most clear within the Reinfjord complex where clinopyroxene—olivine cumulates forming the Lower and Upper Series are cut discordantly by the olivine cumulates of the Central Series. The regularity of the modal layering within the Lower and Upper Layered Series and the recognition of three marginal zones equivalent in time to the major cumulate subdivisions of the complex show that the cumulate sequences represented in the complex have resulted from fractional crystallization of essentially liquid magmas.

The cyclic units which have been distinguished within each of the layered series give evidence of the repeated emplacement of pulses of magma. During the formation of the Lower and Upper Layered Series each emplacement of new magma resulted in the temporary precipitation of olivine on the floor of the magma chamber followed by the cotectic crystallization of clinopyroxene and olivine. Later magmas must have been either appreciably more magnesian or more voluminous and capable of sustaining extended periods of olivine fractionation as witnessed by the volume of dunite and wehrlite represented in the Central Series. Thick sequences of olivine cumulate may, however, be present beneath the Lower or Upper Layered Series and clinopyroxene—olivine cumulates could have been developed in connection with the crystallization of the Central Series but have fallen prey to erosion.

A trend toward more olivine-rich rocks can also be discerned in the Seiland—Stjernøy group of ultramafic complexes. The earliest major magmatic event in the Kvalfjord complex resulted in the emplacement of olivine clinopyroxenite. Wehrlite dykes clearly represent a subsequent episode of activity. The Melkvann and Nordre Bumannsfjord complexes show complex emplacement histories and a wide variety of magmatic phenomena but also here olivine clinopyroxenite dominates the early magmatic activity and appears to have been followed by dunite and wehrlite. Inhomogeneous, banded and xenolith-rich ultramafic dykes may have resulted from the emplacement of viscous, crystal-charged magmas but the evidence in many dykes for extensive wall-rock reaction and assi-

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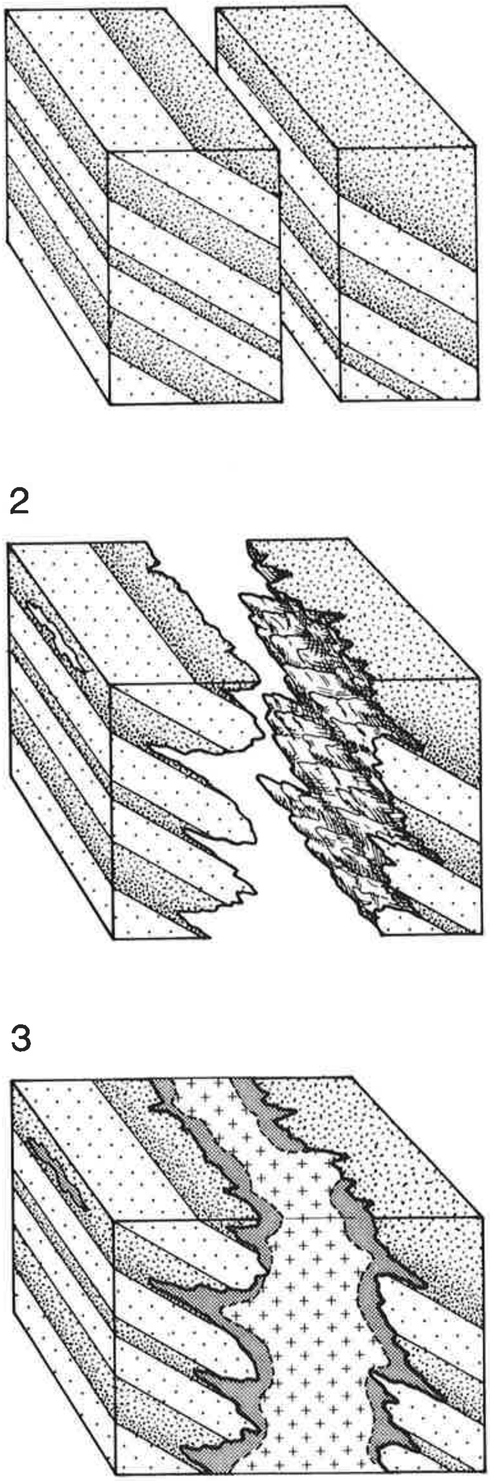

milation as well as their dilational form and often restricted widths suggests the emplacement of fluid magmas. Initial short-lived fractionation of olivine resulted in the dunite and wehrlite which commonly lines contacts of olivine clinopyroxenite dykes (Fig. 34). The later wehrlite dykes were emplaced together with olivine clinopyroxenite and olivine—hornblende clinopyroxenite dykes and may be related to them by fractional crystallization. The appearance at a late stage of numerous amphibole-rich ultramafic dykes and olivine clinopyroxenite dykes bearing Cr-spinel lherzolite and olivine clinopyroxenite nodules appears to be restricted to the Melkvann complex. The waning stages of the magmatic activity represented in the Seiland—Stjernøy complexes were characterized by the emplacement of picritic and ankaramitic dykes which do not seem to be represented in the Reinfjord complex.

Each of the ultramafic complexes is intimately associated with an earlier mafic pluton and it seems probable that the mafic and ultramafic rocks were emplaced *via* common feeder systems. Mineralogical evidence also suggests petrogenetic links between the mafic and subsequent ultramafic rocks. The mafic plutons may be interpreted as parts of major magmatic cycles. The mafic rocks were, however, separated from the emplacement of the ultramafic rocks by an indeterminate interval of time. The gabbros appear to have crystallized, suffered variable degrees of deformation and undergone recrystallization prior to the final emplacement of the ultramafic rocks. The recrystallization appears, however, to be a high-temperature phenomenon, and there is convincing evidence for remobilization of the host gabbros during the emplacement of the Seiland—Stjernøy ultramafic complexes. The lack of chilled facies along contacts of the earliest ultramafic dykes represented in the Seiland—Stjernøy complexes further suggests that the temperature of the host gabbros could not have decreased significantly

Fig. 34. The evolution of irregular olivine clinopyroxenite dykes involved the following stages: 1. The emplacement of magnesian magma into dilational fissures in hot, modally-layered olivine gabbro. 2. Assimilation of the host by the through-flowing magma, the rate of dissolution being controlled by the local composition of the gabbro. 3. Plating of the irregular walls of the enlarged fissure by olivine, forming marginal dunite or wehrlite, followed by the coprecipitation of clinopyroxene and olivine on the smoothed walls, resulting in the olivine clinopyroxenite core.

before the emplacement of the ultramafites. Emplacement of the ultramafic rocks into a high-temperature environment is also suggested by the degree to which reaction, assimilation and hybridization are in evidence within the complexes. Nor is there any evidence of dyking of the host gabbros previous to the emplacement of the ultramafic rocks. This contrasts sharply with the dense swarms of dykes cutting both the gabbros and the ultramafic rocks and the numerous episodes of dyking which appear to have accompanied the earlier evolution of the Seiland magmatic province (Robins & Takla 1979). These considerations suggest to the authors that the emplacement of the ultramafic rocks followed rather rapidly on that of the mafic rocks and may have taken place before the host gabbros were entirely consolidated.

The consecutive development of the mafic plutons and the ultramafic complexes and the intrusive events represented within the complexes can be interpreted as the result of the successive emplacement of magmas having fewer liquidus phases. As noted above, however, early olivine-rich cumulates may possibly be represented beneath the Reinfjord complex and clinopyroxenite—olivine cumulates may have crystallized later than the exposed portion of the Central Series. This reservation applies equally to the gabbroic plutons hosting the ultramafic complexes which could conceivably also be underlain by ultramafic cumulates, although there is little field evidence to support such a conjecture. Considering only the structural level represented by the present-day surface, the initial, voluminous magmas may have had compositions close to the natural plagioclase—clinopyroxene—olivine cotectic. Subsequent magmas were emplaced in diminishing relative volumes and their compositions progressively changed in such a way that they were first close to the clinopyroxene—olivine cotectic surface and later were within the olivine phase volume (Fig. 35). Although detailed consideration of the nature and genetic relationships of the magmas involved in the genesis of the mafic—ultramafic complexes will be deferred to a later contribution, this sequence of intrusive events is worthy of some further general comments. The successive emplacement of rocks whose compositions are related in such a way as to be approximately the reverse of that due to fractional crystallization, such as can be deduced from the Langstrand gabbronorite/Reinfjord complex and the other mafic—ultramafic complexes in the Seiland magmatic province, we term A *regressive intrusive sequence.* A regressive sequence in which a magma which crystallized a thick series of clinopyroxene—olivine cumulates overlain by clinopyroxene—magnetite cumulates was followed by the emplacement of a largely liquid magma from which olivine and chromite were the first minerals to crystallize is represented in the Duke Island ultramafic complex (Irvine 1974). Irvine (1974) suggests a number of possible reasons for this regressive intrusive sequence:

1) Magmas rising along a feeder system heated by the passage of earlier magmas may be less subject to fractional crystallization as they ascend.
2) Later magmas carried olivine in suspension, possibly including some derived from earlier cumulates deposited within the feeder system.
3) Magmas may have been derived from progressively greater depths in the mantle or from a source region that became depleted in water.
4) The composition of the mantle source may have become enriched in olivine due to earlier episodes of partial melting.

A rather different hypothesis for the generation of regressive intrusive sequences in complexes in which the major units are cumulates is upward migration of successive magma chambers such that later cumulate sequences at a particular structural level represent earlier fractionation stages. Regressive intrusive sequences may also be envisaged as a result of the successive tapping of a deep-seated magma chamber which possessed a vertical chemical zonation due to density differences. Evidence bearing on the application of these hypotheses to the Finnmark mafic—ultramafic complexes will be reviewed in the second contribution in this series.

Assimilation

Evidence for local assimilation of the gabbroic hosts is widespread in all complexes and has two main expressions.

1) The form of intrusive contacts.
2) The occurrence of hybrids resulting from the crystallization of syntectic magmas.

In the Melkvann complex the highly irregular, non-dilational contacts of the earliest ultramafic and olivine melagabbro bodies are interpreted as due to local dissolution, the modal variations in the host olivine gabbro having determined the rate at which assimilation took place (Fig. 34). The dykes and sheets represented in this com- plex show a clear tendency towards simpler contact relationships, suggesting that the importance of assimilation diminished with time. This trend culminated in the dilational, chilled contacts of the late-stage picritic and ankaramitic dykes. It is concluded that the intrusive activity within the Melkvann complex took place as temperatures waned. The early phases of intrusion occurred while the envelope remained at such a high temperature that assimilation was promoted. Later, the temperatures within the complex had fallen and assimilation was less marked.

The serrated dyke margins typical of the early intrusions in the Melkvann complex are reproduced on a larger scale along parts of the contacts of the Reinfjord ultramafic complex. The development of websterite and olivine websterite along these contacts and around gabbroic xenoliths buried within cumulates, appears to be the result of crystallization of hybrid magmas which arose by the assimilation of either gabbro or gneiss. Olivine melagabbro found in places around the complex would appear to represent a higher degree of assimilation.

Olivine melagabbro, common within the earliest intrusions in the Melkvann complex and locally developed in the Kvalfjord complex,- appears to be a hybrid which crystallized simultaneously with the olivine clinopyroxenite into which it grades. Minor amounts of olivine melagabbro also occur along the margins of some of the later, irregular olivine clinopyroxenite dykes in the Melkvann complex. Zones of olivine clinopyroxenite and patches of coarse-grained clinopyroxenite along the margins of wehrlite dykes in the Melkvann and Kvalfjord complexes may also be interpreted as a result of assimilation of the olivine clinopyroxenite hosts.

According to Sturt et al. (1980), assimilation played the principal role in the origin of the petrographic variations within the Nordre Bumannsfjord ultramafic complex. They appeal to large-scale interaction of a primary dunite magma with gabbro and metasediment of the envelope and interpret 60—70% of the ultramafic rocks as hybrids. The present authors regard assimilation on this scale is unlikely and reject a dunite liquid as the primary magma. The model does not adequately account for either the composition of the olivine clinopyroxenite within the northern group of ultramafic complexes or its preponderance.

The extreme view advanced by Sturt et al. (1980) of the Reinfjord olivine clinopyroxenites and wehrlites as crystallization products of a syntectic magma is also not compatible with the evidence that they originated as cumulates from an essentially liquid magma. They suggest that a primary dunite magma generated the olivine-rich rocks in the core of the complex. That these are olivine cumulates with intercumulus clinopyroxene suggests, however, that they crystallized from a magma not far removed from the natural clinopyroxene—olivine cotectic.

Metasomatism

The results of metasomatic activity associated with the emplacement of ultramafic rocks can be observed in all of the ultramafic complexes. Both the gabbroic envelopes and earlier ultramafic rocks have been transformed locally and to varying degrees.

The appearance of coarse-grained olivine in originally olivine-free gabbronorite within a few metres of the margin of the Reinfjord complex is a particularly stiking example of metasomatism of envelope rocks. Similar phenomena are known from the Seiland—Stjernøy complexes where extreme local alteration of olivine gabbro resulted in coarse-grained olivine-rich troctolitic gabbro and troctolite varying to dunite. The patchy emplacement of gabbro has resulted in relationships resembling the haloes developed around peridotite dykes within the Emigrant Gap ultramafic complex, California (James 1971). The olivine neoblastesis in the North Norwegian complexes appears to be restricted to zones a few decimetres to metres wide along contacts with ultramafic rocks, the 'flooding' of gabbroic rocks by olivine having only taken place where the mafic rocks are surrounded on all sides by ultramafic rocks. The processes leading to the transformation of gabbro to more olivine-rich rock types thus appear to have operated over a short range and possibly were diffusion controlled.

Although the metasomatic zones may differ significantly in detail from place to place the most common alteration of olivine gabbro appears to be a volume for volume replacement involving a reduction in the mode of clinopyroxene and a corresponding increase in the amount of olivine, and in some cases plagioclase, accompanied by an increase in grain size. The mode of olivine may subsequently increase at the expense of plagioclase. A detailed explanation of this zonation will not be attempted here but the main features of the modal variations can be regarded as an approach towards equilibrium with nearby magmas which were crystallizing only olivine. This is clearly demonstrated by the extensive constant-volume replacement of clinopyroxene by olivine in modally—olivine cumulates around the Central Series of the Reinfjord complex. The irregular development of secondary wehrlite and dunite from pre-existing olivine clinopyroxenite is also widespread in parts of the Melkvann and Kvalfjord complexes, in association with discrete wehrlite dykes. The metasomatic dunites and wehrlites of the North Norwegian ultramafic complexes resemble in many respects the replacement dunites and peridotites described from the Duke Island ultramafic complex, Southeast Alaska (Irvine 1974).

Intrusion mechanisms

One of the principal distinctions between the Seiland—Stjernøy ultramafic complexes and the Reinfjord complex is the structural relationships of the ultramafic rocks with the gabbroic envelopes. The cumulates exposed in the Reinfjord complex clearly must have accumulated within a magma chamber of substantial horizontal cross-section and vertical extent. The observations require, however, a more complex scenario embracing three successively developed chambers, the latest having evolved mainly within the fractionation products of two earlier magma chambers. The events which led to the formation of these magma chambers are nevertheless by no means clear. Structural evidence of the shouldering aside of the country rocks is lacking and the frequency of gabbroic xenoliths within both the marginal zones and layered series suggests that emplacement was accompanied by upward or downward stoping. Dilation may also have played an important role in the development of the chambers. This is suggested by the dyke-like southern extension of the Central Series as well as the subconcordant screen of gabbro forming the local roof and floor of the Lower and Upper Layered Series, respectively. As noted above, assimilation of the envelope took place along the contacts of the complex and must have resulted in enlargement of the magma chambers. Although the available evidence does not permit a detailed description of the evolution of the Reinfjord complex with respect to the room problem, emplacement by dilational mechanisms accompanied by supplementary stoping and assimilation is considered most likely.

In strong contrast to the Reinfjord complex, the Seiland—Stjernøy complexes give little evidence of the existence of large magma chambers. Modal layering is restricted to certain small ultramafic bodies and picritic dykes. Furthermore, the margins of the complexes are commonly gradational with an inwardly increasing frequency of ultramafic dykes and sheets. Much of these complexes appear to have evolved by the recurrent emplacement of dykes and sheets, gradually fragmenting the envelope and resulting in the isolation of country-rock enclaves. Emplacement of the later intrusions was clearly accompanied by dilation while assimilation of the envelope appears to have been important during the earliest phases of development. Initiation of the early intrusions by dilation is considered probable, their subsequent enlargement and replacive structural relationships following from the dissolution of the wall rocks by actively flowing magma (Fig. 34).

Fractional crystallization

Evidence for fractional crystallization in the Reinfjord ultramafic complex is both explicit and dramatic. As noted above, the Lower and Upper Layered Series resulted mainly from the coprecipitation of clinopyroxene and olivine with the temporary fractionation of olivine alone following the ingress of new pulses of magma. The exposed part of the Central Series is composed exclusively of olivine cumulates. The subalkaline affinity of the parent magmas to the Reinfjord cumulates is indicated by the presence of intercumulus Ca-poor pyroxene and the composition of the cumulus clinopyroxene (Bennett 1972, 1974).

Within the Seiland—Stjernøy complexes, field evidence for the operation of fractional crystallization in the genesis of the ultramafic rocks is not obvious. In the Melkvann complex the occurrence of modal layering in one dunite body suggests fractionation of olivine and picotite.

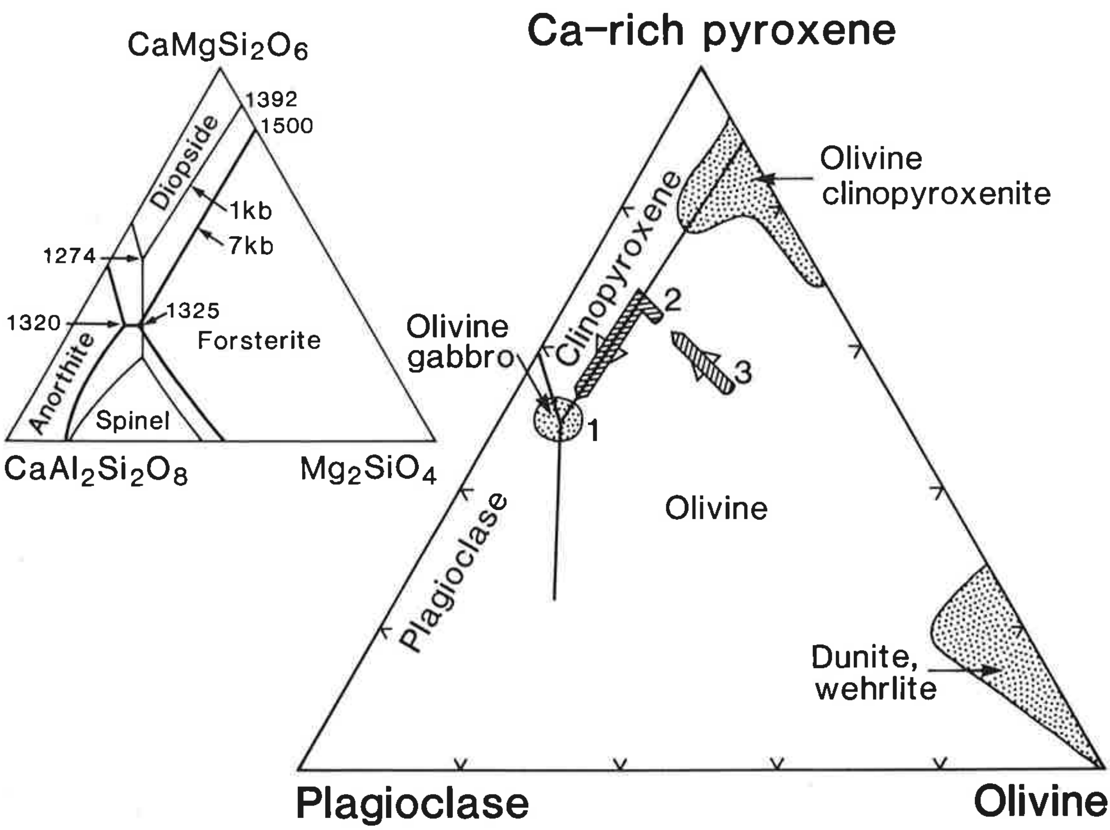

Fig. 35. Preliminary, qualitative, petrogenetic model for the mafic—ultramafic complexes within the Seiland province based on the pseudo-ternary Fo-Di-An system at 1 Kb (Presnall et al. 1978). Initial voluminous magmas had compositions close to the natural plagioclase—clinopyroxene—olivine cotectic (field 1). Subsequent magmas were more magnesian and underwent fractional crystallization along path 2, forming olivine clinopyroxenite and minor amounts of wehrlite and dunite. The most magnesian magmas crystallized dunite and wehrlite while evolving along path 3. The expansion of the diopside field with increasing pressure (see inset) suggests that a wider range of natural liquids will precipitate olivine followed by clinopyroxene at moderate pressure than a lower pressure.

Late picrite dykes, containing mineral lamination accompanied in some cases by modal layering and cyclic units, resulted from fractional crystallization of magmas which probably were emplaced laterally along these surprisingly narrow dykes. Mineral chemistry and the crystallization sequence suggests that the picrite dykes are cogenetic with the bulk of the ultramafic rocks within these complexes. Early olivine fractionation is proposed for the dunite and wehrlite which common lines the walls of olivine clinopyroxenite dykes (Fig. 34). Narrow wehrlite dykes containing laminated olivine are also believed to be due to the precipitation of olivine from magmas migrating laterally along dilational fractures.

The modal compositions of the main rock types in the Seiland—Stjernøy complexes probably constitute the most persuasive evidence of an origin by fractional crystrallization. Olivine clinopyroxenite, the dominant rock type, contains clinopyroxene and olivine in proportions similar to those predicted by the iron-free Fo—Di—An pseudo-ternary system at moderate pressure (Presnall et al. 1978) for the cotectic crystallization of forsterite and diopside (Fig. 35). The wehrlite and dunite intrusions can also be satisfactorily explained by the accumulation of olivine followed by varying degrees of intercumulus crystallization of clinopyroxene. For these principal reasons we suggest that the ultramafic rocks forming the bulk of the Seiland—Stjernøy complexes are cumulates. In dykes the cumulates may have been generated by plating of the walls or precipitation on the floors of conduits through which magma was moving for prolonged periods. Crystal accumulation was assisted by the low viscosities of the magnesian, ultrabasic magmas and the high temperatures of the mafic plutons into which they were emplaced. The normative compositions of the Seiland—Stjernøy ultramafic rocks and the Ca- and Al-contents of their clinopyroxene (Oosterom 1963, Yeo 1984, unpublished data) suggest derivation from critically undersaturated magmas. As pointed out by Irvine (1974), magmas with significantly different initial compositions may yield similar ultramafic rocks as early fractionates. This appears to be borne out by the ultramafic rocks of the Reinfjord and Seiland—Stjernøy complexes.

A notable feature of the Fo—Di—An 'system' is the expansion of the stability fields for clinopyroxene and spinel at the expense of forsterite and anorthite as the pressure increases (Presnall et al. 1978). The reduction of the plagioclase field is enhanced by the presence of water (Yoder 1965) as well as Na_2O (Biggar 1983). These relationships suggest that at moderate pressure a far wider range of natural liquids will crystallize olivine followed by clinopyroxene than at lower pressures where olivine and then plagioclase is a common crystallization sequence in magmas of 'basaltic' composition (Fig. 35). Furthermore, for liquids of equivalent composition the experimental observations suggest that the coprecipitation of clinopyroxene and olivine can be take place over a wide temperature interval at moderate pressure than at low pressure. These generalisations can explain the abundance of olivine clinopyroxenite in the ultramafic complexes of North Norway, emplaced at depths corresponding to 6—10 Kb.

A radically different interpretation of the Nordre Bumannsfjord ultramafic complex was advanced by Sturt et al. (1980). They regarded the ultramafic and related rocks as derived from dunite liquids, emplaced at temperatures higher than 1650°C, through varying degrees of assimilation of host rocks and mixing with anatectic melts. Narrow dykes, sheets and veins of dunite and peridotite are viewed as the result of the *in situ* crystallization of magmas of equivalent composition, while late-stage mafic dykes are supposed to represent anatectic melts derived from gabbroic xenoliths deeper in the complex. The present authors find little merit in these concepts. The relatively minor volume of dunite within the Seiland—Stjernøy complexes does not support a parental dunite magma, nor do the field relationships appear to demand such extreme magma compositions or temperatures. The development of the ultramafic complexes within the Seiland magmatic province of North Norway appears to the present authors to have involved a variety of mantle-derived magmas, the most magnesian of which were probably picritic, with up to c. 20 wt. % MgO and emplaced at temperatures of c. 1450°C (Yeo 1984, Emblin 1985). Some of these magmas may be represented among the picrite—ankaramite dykes which cut the Seiland—Stjernøy ultramafic complexes. A detailed discussion of petrogenetic models based on rock and mineral chemistries will, however, be presented in the second paper in this series.

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