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The Seiland Igneous Province, North Norway.
Field Trip Guidebook, IGCP project 336.

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Summary:

Field trip guidebook prepared for the International Geological Correlation Program (IGCP) Project 336: Field conference and symposium on Layered Mafic Complexes and related ore deposits of Northern Fennoscandia: Finland, Norway and Russia August 18-31, 1996.

Contains a comprehensive description of the general geology and magmatic evolution of the Seiland Igneous province in addition to a guide to 10 localities in the Hakkstabben-Altneset area of Seiland.

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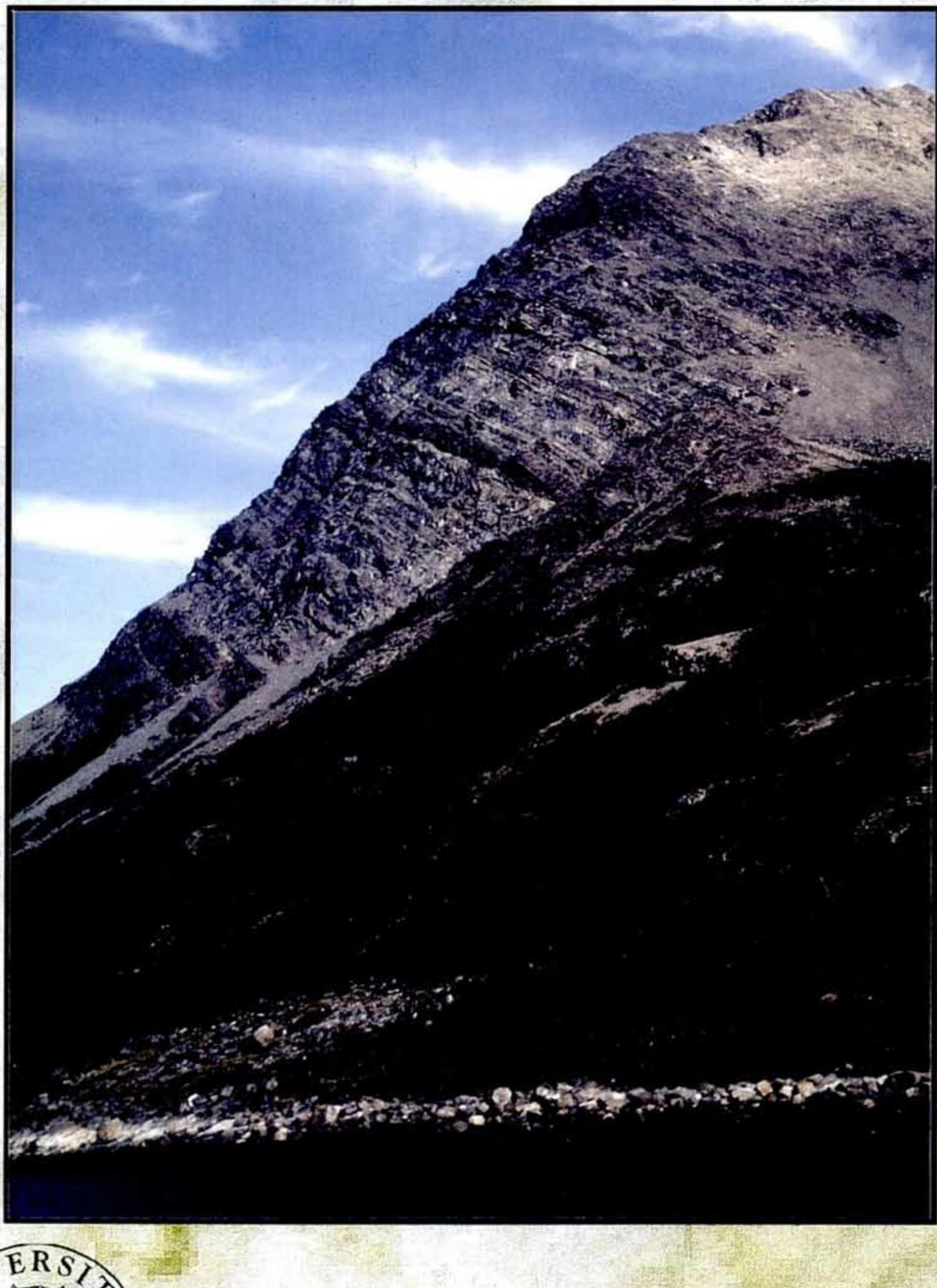
FIELD TRIP GUIDEBOOK

THE SEILAND IGNEOUS PROVINCE, NORTH NORWAY



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Norges geologiske undersøkelse
Geological Survey of Norway

FIELD TRIP GUIDEBOOK

Part II:

THE SEILAND IGNEOUS PROVINCE, NORTH NORWAY

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Layered Mafic Complexes and Related Ore Deposits of Northern Fennoscandia:
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International Geological Correlation Program

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PETROLOGY AND METALLOGENY OF
INTRAPLATE MAFIC AND ULTRAMAFIC MAGMATISM

1996 Field Conference and Symposium

Layered Mafic Complexes and Related ore Deposits of Northern Fennoscandia

August 18-31, 1996

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Contents

THE SEILAND IGNEOUS PROVINCE, N. NORWAY: GENERAL GEOLOGY AND MAGMATIC EVOLUTION

B. Robins

1. Introduction

The Seiland Igneous Province is a unique feature of the Kalak Nappe Complex of the North Norwegian Caledonides, and the interpretation of its complex structural, magmatic and metamorphic geology presents special problems. Nevertheless, the province has had a particular significance for models for the development of the Caledonian orogeny in Scandinavia: It was mainly on the basis of experience within the confines of the province that the hypothesis of a "Finnmarkian Orogeny" was formulated by Sturt, Ramsay and co-workers (Sturt *et al.* 1978, Ramsay *et al.* 1985, Ramsay & Sturt 1986). This hypothesis has had to be revised as isotopic data from the various igneous rocks has accumulated, and new interpretations are currently emerging regarding the age of magmatic, tectonic and metamorphic events as well as the tectonic environment in which the magmatic activity took place. Recent results suggest that much of the magmatism took place in connection with Riphean to Middle Cambrian intracontinental rifting.

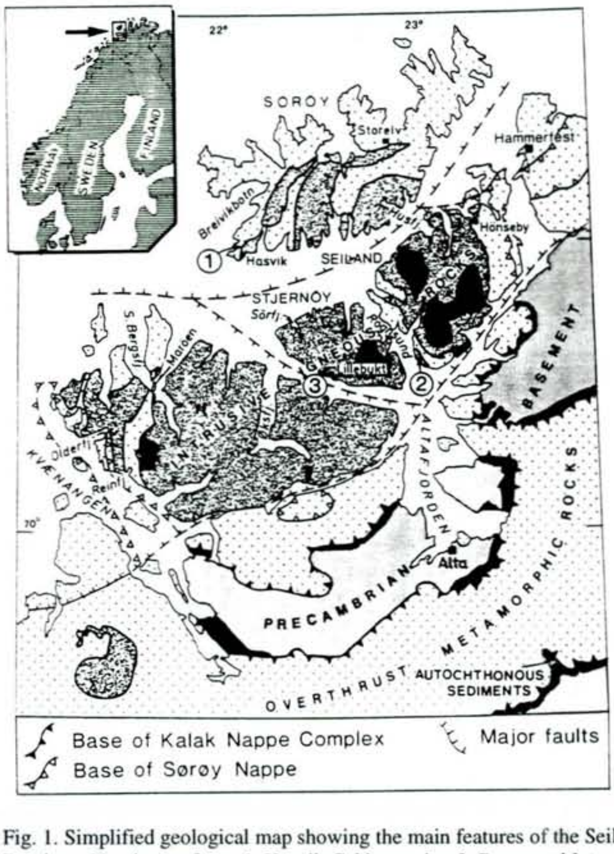

Fig. 1. Simplified geological map showing the main features of the Seiland Province. Numbers refer to 1. Hasvik Gabbronorite; 2. Rognsund Intrusion; 3. Lillebukt Alkaline Complex. Ultramafic complexes are in black.

Exploration for economic Fe-Ti-V ores, Ni-Cu ores and apatite deposits carried out in the Seiland Igneous Province has met with little success. The province is known to contain large, low-grade Fe-Ti deposits within gabbro intrusions as well as substantial low-grade apatite concentrations in carbonatite and hornblende pyroxenites within the Lillebukt Alkaline Complex. Current mining activity is limited to the very successful exploitation of nepheline syenite at Lillebukt by North Cape Minerals for use in the production of ceramics and glass. Blocks of nepheline syenite from Lillebukt and gabbro from Hasvik have also been marketed for ornamental purposes.

2. Regional geology

The Seiland Igneous Province (SIP) is contained within the Sørøy Nappe of the Kalak Nappe Complex which constitutes part of the Middle Allochthon of the North Norwegian Caledonides. The Kalak Nappes were thrust from the WNW into their present position above the Karelian basement and its cover of autocthonous or semi-autochthonous Late Precambrian to Cambrian sediments exposed in antiformal windows on the mainland (Roberts & Gee 1985) (Fig. 1).

The coastal region of West Finnmark is cut by a series of major faults and the SIP appears to occur within a series of fault blocks that are successively downthrown to the NW. The SIP is limited to the SE by the NE-SW trending Kvænangen-Langfjord-Vargsund fault. Sørøya probably forms a separate fault block that exposes rocks from a higher structural level than the rest of the SIP.

The Kalak nappes typically repeat lithological couplets, in which the lower unit is composed of either orthogneiss or paragneiss and the upper unit consists of either Karelian rocks of the Raipas Supergroup or the distinctive metasedimentary sequence of the Sørøy Group. Primary unconformities between the two units are preserved locally in the region (Ramsay & Sturt 1977, Ramsay *et al.* 1979, 1985). In the case of the Sørøy Group a basal unconformity has been recorded

Table 1. Generalised (tectono)stratigraphy of the Sørøy Nappe (mainly after Ramsay 1971 and Roberts 1968). The nomenclature is purely informal.

Principal stratigraphic units	Lithologies
SØRØY GROUP:	
Hellefjord Formation (≥700-900m)	Pelitic schists and psammites
Åfjord Formation (only distinguished in SW Sørøy, elsewhere included in Falkenes Fm)	Graphitic schist, calc-silicate, white, granular psammite at top.
Falkenes Formation (≅60m)	Marble and calc-silicates
Storelv Formation (≅110m)	Muscovite schist, minor psammite
Klubben Formation (≅3400m)	Psammite (cross-bedded in places), minor pelitic schist
Conformity, unconformity or tectonic break	
EIDVÅGEID SUPRACRUSTAL SEQUENCE	Paragneiss (migmatitic pelitic and quartzofeldspathic gneiss, quartzite, marble and calc-silicate rocks)

in several places, but only with orthogneisses of the Fagervik Infracrustal Complex.
The Sørøy Nappe is the uppermost, and presumably the most far-travelled of the Kalak nappes and is characterised by a couplet of paragneiss and the Sørøy Group. The lower stratigraphic unit of the Sørøy Nappe, the Eidvågeid Supracrustal Sequence, has its type area in NE Seiland (Akselsen 1980, 1982) and is also exposed in the southern part of the Seiland Province, on the Øksfjord peninsula (and possibly also on Sørøya according to Rice 1990). It comprises migmatitic, sillimanite-orthoclase facies pelitic, semipelitic and quartzofeldspathic gneiss, as well as minor quartzite, marble and calc-silicate rocks. There is presently little evidence that the Eigvågeid Supracrustal Sequence is a previously-deformed basement on which the Sørøy Group was deposited, and it may represent the lowest part of a continuous stratigraphic sequence.

The structurally-overlying Sørøy Group occurs on the westernmost part of the Øksfjord peninsula as well as on Sørøy and consists of a sequence of psammites, schists, marble and calc-silicates that records a transition from predominantly shallow-water, clastic deposition to turbidite-type sedimentation (Roberts 1974, Ramsay *et al.* 1985) (Table 1). The sequence was believed to include middle Cambrian and younger rocks on the basis of archeocyathids identified in marble belonging to the Falkenes Formation (Holland & Sturt 1970), but this identification seems to have been erroneous (Debrenne 1984).

3. The tectonic and metamorphic evolution of the SIP

According to Ramsay *et al.* (1985), the main orogenic deformation of the Sørøy Group took place during two principal phases (D1 and D2), each initiated by episodes of folding and thrusting and succeeded by the imposition of flattening strains, possibly related to gravitational spreading following nappe translation. The peak of the regional metamorphism was reached between the two phases of deformation when Barrovian, kyanite- and sillimanite-grade mineral assemblages developed, and temperatures waned during the D2 deformation. The first phase of deformation was the most intense and resulted on Sørøy in major, recumbent, near-isoclinal, noncylindrical folds and a strong fabric. The second phase of deformation generated folds that vary both in scale and symmetry. There is also local evidence for a third phase of fold generation (D3) that resulted in large-scale, asymmetrical, open folds.

The deformation and metamorphism of the Sørøy Group has been assigned to an early phase of the Caledonian Orogeny (Sturt *et al.* 1978, Ramsay *et al.* 1985), referred to as the "Finnmarkian Orogeny" (Ramsay & Sturt 1986). The latter, as originally proposed on the basis of structural, metamorphic and magmatic relationships in the SIP, was only very poorly constrained in time. Rb-Sr whole-rock isochrons from intrusions and contact metamorphic aureoles suggested that it occurred at about 540-490 Ma (Sturt *et al.* 1978).

The concept of the Finnmarkian Orogeny is closely linked to the interpretation that the magmatic activity in the Seiland Province was synorogenic (Sturt *et al.* 1978, Ramsay & Sturt 1986). This was based on field observations, for instance that foliated igneous intrusions are cut by younger intrusions that were themselves overprinted by later metamorphic fabrics. According to Sturt & Ramsay (1965) and Sturt *et al.* (1978), the late-stage alkaline igneous rocks in the province were both intruded and deformed during the latest stages of D2, the youngest phase of Finnmarkian deformation in the Sørøy Nappe. Nepheline from nepheline syenite pegmatites has yielded K-Ar ages of circa 490 Ma (Sturt *et al.* 1967), and these have been interpreted as dating passage through the nepheline "closure temperature" during uplift and erosion of the Finnmarkian Orogen (Sturt *et al.* 1978, Ramsay & Sturt 1986). Hornblende from the lower part of the Sørøy Nappe also gives ^{40}Ar-^{39}Ar plateau ages of 490 ± 5 Ma (Dallmeyer 1988). However, nepheline and hornblende from the alkaline rocks of the SIP give ^{40}Ar-^{39}Ar plateau ages of circa 431-425 Ma (Dallmeyer 1988), compatible with the K-Ar biotite ages and the Rb-Sr biotite age reported from similar rocks by Sturt *et al.* (1967,1978). The ^{40}Ar-^{39}Ar and K-Ar ages may reflect the superposition of a Late Cambrian-Early Ordovician tectonothermal event and a lower-grade, Silurian metamorphism (Dallmeyer 1988).

The first U-Pb ages from zircons and titanite from nepheline syenite pegmatites of 523-531 Ma (Pedersen *et al.* 1989) gave a new and much more precise constraint on the age of the youngest phase of the Finnmarkian Orogeny, as defined by Sturt *et al.* (1978), near the Middle-Late Cambrian boundary in the Harland *et al.* (1982) time scale. However, the U-Pb data in combination with Sm-Nd and Rb-Sr isochrons from gabbroic plutons (Aitcheson 1989, Krogh & Elvevold 1990, Daly *et al.* 1991) have led to a radical revision of views on the history of the Seiland Province. Sm-Nd internal isochrons from the Hasvik Gabbronorite (Fig. 1) gave crystallisation ages of ~700Ma. This intrusion can be demonstrated from field relations to post-date the D1 fabric as well as D2 and D3 folds in the host rocks. Thus the "Finnmarkian" deformation and metamorphism must be much older (>700Ma) than was previously supposed, while the alkaline rocks were deformed and recrystallised in the interval between 521 and 490Ma. It now appears that emplacement of the igneous rocks in the SIP took place during a long period of time, between >830Ma (the Rb-Sr isochron age of a gabbro/monzonite intrusion near Øksfjord) and 520Ma.

A summary of the authors present interpretation of the tectonic and metamorphic evolution of the province is presented in Table 2. Note that in order to maintain consistency with published accounts, the informal term "Finnmarkian Orogeny" is used for a possible Late Cambrian-Early Ordovician tectonothermal event, as yet poorly constrained by field relationships and radiometric ages, while the principal tectonic and metamorphic events recorded within the SIP are assigned to a Late Proterozoic "Sørøyan Orogeny" (equivalent to the Porsanger orogeny of Daly *et al.* (1991).

A point of issue at present regards the relationship between plutons in the Seiland Province and the Sørøy Group. Rice (1990) has suggested that metasediments belonging to the Eidvågeid Supracrustal Sequence are present on Sørøya structurally beneath the Sørøy Group, and that the Hasvik Gabbronorite (and other plutons) may be emplaced only into this unit rather than into the Klubben formation as previously believed. In addition, the post-D2 Litlefjord Granite on Porsangerhalvøya (dated by the U-Pb method on zircons to 804 ± 19Ma, Daly *et al.* (1991) may also be emplaced into the Eidvågeid Supracrustal Sequence. If these interpretations are correct, then the evidence for a Late Proterozoic orogeny affecting the Sørøy Group is effectively eliminated. At the moment there is no compelling evidence (e.g. that it exhibits a more prolonged tectonothermal evolution) that the Eidvågeid S.S. is significantly older than the Sørøy Sequence, or that the SIP plutons intrude only the Eidvågeid S.S.

A currently unresolved problem concerns the age and significance of the high-grade metamorphic parageneses i.e. pyroxene granulite that is developed from many of the gabbroic plutons in the SIP, and garnet granulite mineral assemblages that developed in shear zones in gabbro on the Øksfjord peninsula (corresponding to metamorphic stages 2 and 3 of Elvevold (1990) and Elvevold *et al.* (1994) in the Øksfjord area) and elsewhere. According to Mørk & Stabel (1990) a Sm-Nd internal isochron from the Storvik Metagabbro, Øksfjord, dates the garnet granulite facies metamorphism (possibly equivalent to stage 2 of Elvevold 1990), under conditions of 640-670°C and 5-7 kb, to 502±28 Ma, an age that is similar to that for the emplacement of the alkaline rocks on Seiland and Stjernøya as given by the U-Pb method. A garnet-bearing felsic granulite from Klubbneset, Øksfjord yielded a Sm-Nd isochron (essentially a garnet age) of 531±10 Ma (Mørk & Stabel 1990), roughly contemporaneous with the emplacement of the alkaline pegmatites elsewhere in the Seiland Province. The mafic garnet granulites indicate that a phase of high-pressure metamorphism took place at a late stage in the plutonic history of the SIP. This took place at about the same time as eclogite-facies metamorphism in the Seve Nappes (~505 Ma, Mørk *et al.* 1988) and may be related to Late Cambrian-Early Ordovician subduction. There is no evidence, however, that the mafic dykes emplaced into, and deformed together with the alkaline rocks in the SIP have been metamorphosed in the granulite facies.

An important tectonic feature of the SIP not accounted for by the orogenic deformation represented by D1, D2 and D3 is the occurrence of large synformal structures centred around mafic and ultramafic plutons. One of these synforms controls the outcrop pattern over much of the island of Seiland. The fold affects the dominant fabric in the country rocks as well as the modal layering and the layer-parallel tectonic foliations that are present in several of the gabbroic plutons that are deformed by it. The Melkvann Ultramafic Complex occurs in the core of this synform and does not exhibit any tectonic overprint. Swarms of nepheline syenite pegmatite dykes on the southern part of Seiland cut across both the Melkvann U.C. and the synform, and were clearly emplaced after the formation of the fold. Several synforms similar to the Seiland Synform occur in the SIP. One of these dominates the structure of Stjernøya and the area between Øksfjord and Langfjord, another occurs to the east of the Reinfjord U.C.. These large synforms are believed to have formed by the foundering of individual large plutons after their crystallisation into underlying, less-dense, plastic rocks (Glazner 1994). Essentially gravity-driven, the synforms (and the complementary antiforms) are regarded as a consequence of the magmatic activity and do not imply any crustal shortening. A recent structural study of the synformal Bjerkreim-Sokndal Intrusion (Rogaland, SW Norway) has demonstrated that metamorphic foliations and lineations can develop in the igneous rocks and the adjacent country rocks as foundering proceeds (Paludan *et al.* 1994) This study suggests that the foliations that overprint the magmatic textures in many of the Seiland mafic plutons may be related to localised vertical tectonics and not to orogenic events as previously believed. This interpretation also casts doubt on whether foliations in particular plutons or areas have any regional tectonic significance, and also whether radiometric ages of metamorphic mineral assemblages in plutons date anything other than gravitational collapse. The locally very intense deformation of the alkaline igneous rocks in the SIP and the contemporaneous mafic dykes, almost certainly cannot be attributed to foundering of

Table 2. A possible interpretation of the evolution of the Seiland Province

TIME	GEOLOGICAL EVENTS	RADIOMETRIC EVIDENCE
LATE SILURIAN - EARLY DEVONIAN	*SCANDIAN OROGENY.* EMPLACEMENT OF NAPPES, LOW-GRADE METAMORPHISM	K-Ar (micas): 390-430 Ma. Ar-Ar (hble.) & (neph.): 425-431 Ma.
LATE CAMBRIAN - EARLY ORDOVICIAN	REGIONAL DEFORMATION, MEDIUM TO HIGH-GRADE METAMORPHISM AT INTERMEDIATE CRUSTAL DEPTHS (*"FINNMARKIAN OROGENY"*)	K-Ar (nepheline): 491-480 Ma. Ar-Ar (hble.): 490 ± 5 Ma. Sm-Nd isochron: 502±28 Ma (mafic garnet granulite, Øksfjord),
	SUBSIDENCE/BEGINNING OF SUBDUCTION?	
MIDDLE CAMBRIAN	**ALKALINE & BASALTIC MAGMATISM** (AT A SHALLOW CRUSTAL LEVEL?).	U-Pb (zircon): 531 ± 2 & 523 ± 2 Ma (nepheline syenite pegmatites).
	RAPID UPLIFT?	
	CRUSTAL EXTENSION & GRAVITATIONAL TECTONICS, **BASALTIC & PICRITIC MAGMATIC ACTIVITY** AT INTERMEDIATE CRUSTAL DEPTHS, HIGH-GRADE (CONTACT?) METAMORPHISM	Sm-Nd isochrons (intrusion): 706±37 Ma (Hasvik Gabbronorite) - 513±24 Ma (Lille Kufjord Intrusion). Sm-Nd isochron (metamorphism): 531±10 Ma (felsic granulite, Øksfjord).
LATE PROTEROZOIC	MAIN REGIONAL DEFORMATION & HIGH-GRADE METAMORPHISM OF SØRØY GROUP, **CALC-ALKALINE MAGMATISM** (*"SØRØYAN OROGENY"*)	U-Pb (zircon): 804±19 Ma (post-D_2 granite*). Rb-Sr isochron: 829±18 Ma (Gabbro/monzonite intrusion, Øksfjord).
	DEPOSITION OF SØRØY GROUP ON ARCHAEAN ORTHOGNEISS (FAGERVIK INFRACRUSTAL COMPLEX) & POSSIBLY ON LATE PROTEROZOIC PARAGNEISS (EIDVÅGEID SUPRACRUSTAL SEQUENCE)	Nd model age: 1.7-1.2Ga (Sørøy Group). Nd model age: 1.7-1.2Ga (Eidvågeid S.S). Nd model age: 2.7Ga (Fagervik I.C.)

* Litlefjord Granite, within the Havvannet Imbricate Stack on Porsangerhalvøya (Daly *et al.* 1991).

Table 3. Major igneous intrusions in the Seiland Igneous Province.

Youngest intrusions	References
Syenite & nepheline syenite pegmatites	Sturt & Ramsay (1965), Pedersen *et al.* (1989)
Breivikbotn Alkaline Complex (Sørøya)	Sturt & Ramsay (1965)
Lillebukt Alkaline Complex (Stjernøya)	Heier 1961, Robins (1980)
Pollen Carbonatite (Stjernøya)	Robins & Tysseland (1983)

Younger plutons	References
Lille Kufjord Intrusion (Seiland)	Robins *et al.* (1991)
Melkvann, Nordre Bumannsfjord & Happofjell Ultramafic Complexes (Seiland)	Bennett *et al.* (1986)
Kvalfjord Ultramafic Complex (Stjernøya)	Bennett *et al.* (1986)
Reinfjord Ultramafic Complex (Kvænangen)	Bennett *et al.* (1986)
Tappeluft ultramafic intrusion (Øksfjord Peninsula)	Mørk & Stabel (1990)
Vest Borgastak peridotite (Sørøya)	Bjerkenes (1975)
Vest Borgastak olivine gabbro (Sørøya)	Bjerkenes (1975)
Rognsund olivine gabbro (Seiland)	Robins 1982
Melkvann olivine gabbro (Seiland)	Bennett *et al.* (1986)
Kvalfjord olivine gabbro (Stjernøya)	Bennett *et al.* (1986)
Storvik olivine gabbro (Øksfjord Peninsula)	Daly *et al.* (1991)
Tappeluft gabbro (Øksfjord Peninsula)	Mørk & Stabel (1990)
Hasvik Intrusion (Sørøya)	Gardner (1980)
Langstrand gabbronorite (Kvænangen)	Hooper (1971), Bennett *et al.* (1986)
Seiland Syenogabbro (Seiland)	Robins & Gardner (1974)

Oldest plutons	References
Havnefjord diorite (Sørøya)	Speedyman (1983)
Øksfjord gabbro-monzonite complex (Øksfjord Peninsula)	Krogh & Elvevold (1990)
Storelv metagabbro (Sørøya)	Stumpfl & Sturt (1965), Sturt & Taylor (1972)
Breivikbotn metagabbro (Sørøya)	Stumpfl & Sturt (1965), Sturt & Ramsay (1965)
Husfjord metagabbro (Sørøya)	Speedyman (1983)
Hønseby metagabbro (Seiland)	Worthing (1971), Akselsen (1982)

plutons, and probably represents the only certain expression of the Caledonian orogeny in the SIP.

4. The magmatic evolution of the SIP

The magmatic evolution of the Seiland Province was prolonged and involved the emplacement of numerous gabbroic plutons, high-K calc-alkaline intrusions, ultramafic complexes, alkaline rocks, carbonatites and swarms of mafic dykes (Robins & Gardner 1975) (see Table 3 for a list of individual named intrusions). Granitoids are volumetrically minor in the SIP as a whole, but locally they are important. The igneous rocks were emplaced in both the Eidvågeid Supracrustal Sequence and the Sørøy Group. They were all initially interpreted as having been intruded during Caledonian polyphasal regional deformation and concurrent Barrovian-type regional metamorphism of the Sørøy Group (Robins & Gardner 1975, and see above).

With the exception of the late-stage alkaline suite and associated intrusions, most of the igneous rocks of the Seiland Province show indisputable evidence for emplacement and cooling at intermediate crustal depth. This is reflected in the compositions of cordierite and garnet in contact-metamorphic aureoles (Bennett *et al.* 1986, Robins *et al.* 1991), the development of 2 pyroxene-spinel symplectites in olivine-bearing gabbro and plagioclase-bearing ultramafic rocks (Gardner & Robins 1974, Robins 1982, Bennett *et al.* 1986) and the formation of garnet-quartz coronas between Fe-rich orthopyroxene and plagioclase in gabbronorites (Akselsen 1980, Gardner 1980).

The Storelv and Breivikbotn intrusions on Sørøya are probably two of the oldest gabbros in the SIP. They are strongly foliated and recrystallised, and are cut by a variety of younger, variably-deformed, diorite, monzonite and granitoid intrusions as well as later olivine gabbro, ultramafic rocks and alkaline pegmatites and gneisses. In the Børfjord area the Storelv gabbro is a thin sheet that has a penetrative fabric coincident with that of adjacent major D1 isoclines, and is folded by asymmetrical folds identified as D2 structures (Sturt & Taylor 1972). The field relations suggest truly synorogenic magmatic activity, and this is supported by the calc-alkaline association of sub-alkaline gabbro, diorite and granitic rocks.

The later magmatic activity was the most voluminous on Seiland, Stjernøya and the Øksfjord peninsula. It was mixed in character, and individual plutons were derived from tholeiitic, transitional and alkali olivine basalt or picrite magmas. The Hasvik gabbronorite, one of the oldest of the later group of plutons, and the Lille Kufjord Intrusion, the youngest, both exhibit typically tholeiitic mineral compositions and crystallisation sequences. Both of these bodies have field relationships and initial Sr-isotope ratios that suggest that their parental magmas have assimilated exceptional amounts of the metasedimentary host rocks.

Syenogabbro intrusions, characterised by the presence of Ca-poor pyroxene and syenitic differentiates, as well as separate and probably related syenite (perthosite) intrusions, are widespread in the SIP. They are believed to have crystallised from transitional basalt magma.

Some of the largest gabbro intrusions in the SIP are composed largely of olivine gabbros that lack primary Ca-poor pyroxene and are characterised by relatively aluminous Ca-rich pyroxenes. These, and the ultramafic complexes (excepting the Reinfjord U.C.) that are commonly developed within them, were derived from basic and ultrabasic magmas of alkaline affinity, either alkali olivine basalt or alkali picrite magmas.

Alkaline rocks, carbonatites and mafic dykes are clearly the youngest igneous rocks in the Seiland Province. The alkaline rocks are believed to be related to nephelinitic magmatism, while the mafic dykes appear to represent a continuation of alkali basaltic magmatic activity. Field relationships in the Lillebukt Alkaline Complex, Stjernøy (Heier 1961, Robins 1980), and elsewhere demonstrate unequivocally that nepheline syenite pegmatites, distributed widely on Seiland, Sørøy, Stjernøy and the north-western part of the Øksfjord Peninsula, represent the very latest phase of the alkaline magmatic activity. They nevertheless *appear* to be synorogenic in that they were intruded into folded and metamorphosed igneous and sedimentary rocks and were themselves subsequently deformed. It is now recognised, however, that they have been emplaced between two orogenic events widely separated in time.

5. Gabbroic plutons: 3 examples

5.1 The Hasvik Gabbronorite

The Hasvik Gabbronorite (HG) covers an area of about 3x4km on the southern tip of Sørøya. The exposed part is probably only the end of a large pluton extending to the south beneath Lopphavet, as indicated by a large aeromagnetic anomaly. The intrusion is emplaced into the steep limb of a D3 fold that affects psammites and semipelites, probably belonging to the Sørøy Group. Two Sm-Nd mineral isochrons show that the intrusion crystallised at 700±33Ma (Daly *et al.* 1991). The HG is cut by narrow shear zones, granitoid dykes, mafic dykes belonging to at least two generations and composite mafic/granitoid dykes (some of which show evidence of the coexistence of basic and acid magmas).

The contact-metamorphic aureole. The HG has a well-preserved contact metamorphic aureole, ~500m wide on Hasfjordneset. Metasediments in the inner part of the aureole are generally massive, coarse-grained and highly-recrystallised rocks characterised by the occurrence of sillimanite, garnet, orthopyroxene, cordierite and spinel instead of the regional kyanite/sillimanite, garnet, biotite assemblage. They show clear evidence of localised partial melting that gave rise to granodioritic neosomes. Regionally-developed metamorphic foliations and folds that are present in the metasediments in the outer part of the aureole are preserved locally in the recrystallised rocks of the aureole, and show that contact metamorphism post-dated both the D1 fabric and D2 folds. The aureole is cut by later shear zones (these are also common in the gabbronorite itself), granitic pegmatites and post-metamorphic mafic dykes. The shear zones exhibit fine-grained, recrystallised textures and small garnet euhedra, suggesting growth after contact metamorphism.

The internal structure. Cumulates in the HG may be subdivided into a Marginal Border Series (MBS), a Layered Series (LS) and an Upper Border Series (UBS) that crystallised on the walls, floor and roof of a magma chamber.

Modal layering is generally inconspicuous in the ~1600m thick LS but the cryptic variation is extensive and the various cumulus mineral assemblages allow a fairly detailed subdivision. Modal layering and mineral laminations in the HG define an upright, asymmetrical syncline with a NE-SW axis, the most evolved cumulates in the LS and the UBS being preserved in its core.

The ~120m thick Basal Zone consists of laminated gabbronorite with patches of gabbro pegmatite and frequent metasedimentary xenoliths near the base.

The Lower Zone is ~270m thick and characterised by cumulus plagioclase, Ca-rich pyroxene and olivine. Diffuse modal layering is present in the LZ, particularly in its lowest part where there are sequences of melanocratic olivine gabbro and, in places, ultramafic cumulates. Cumulus minerals exhibit a reversed cryptic variation through the BZ and most of the LZ. The most primitive compositions are reached in the upper part of the LZ where plagioclase is ~An_{72} and olivine is ~Fo_{79}.

The disappearance of cumulus olivine and entry of cumulus Ca-poor pyroxene marks the base of the ~1025m thick Middle Zone. The MZ is further subdivided into two subzones (MZa and MZb) separated by the entry of cumulus Fe-Ti oxides. Olivine briefly reappears as a cumulus mineral (but is generally serpentinised or replaced by orthopyroxene-magnetite symplectites) towards the top of MZb. Plagioclase varies from ~An_{62} to ~An_{50} through the MZ while the Mg# of Ca-poor pyroxene varies from ~77 to ~64.

The ~190m thick Upper Zone cumulates contain cumulus apatite and inverted pigeonite. Plagioclase compositions are in the range An_{50-48}. The UZ enclose abundant xenoliths of highly-metamorphosed metasediments.

Only ~5m of the UBS is preserved. It consists of oxide gabbronorite characterised by abundant poikilitic amphiboles.

The smooth, normal cryptic variation in the composition of cumulus minerals from the upper part of the LZ to the top of the UZ is accompanied by a systematic change in initial Sr-isotope ratio (Sr_0), from 0.7038 to 0.7089 (Tegner 1994). The lowest part of the LS also shows an upward decrease in Sr_0, from ~0.7048 in the middle of the BZ.

Petrogenesis. The cryptic regression in the BZ and LZ indicates that these cumulates crystallised from gradually less-evolved and higher temperature magmas, as this part of the chamber was slowly expanding and filling with magma. Thereafter, the magma evolved predominantly by fractional crystallisation in a chamber closed to new magma as cooling progressed and the magma temperature fell. The sequence of crystallisation in the HG (as given by the order in which cumulus minerals make their entries), in particular the cessation of olivine crystallisation and its later reappearance as a liquidus phase, is characteristic of tholeiitic basalt magma that differentiated under relatively low fO_2. The HG magma probably had slightly higher fO_2 and silica activity than the initial Skaergaard magma, as indicated by the compositions of the silicate minerals on the appearance of cumulus magnetite, and the lack of olivine crystallisation during the final stages of solidification.

The initial decrease and then increase in Sr_0 suggests that the magma that initially flowed into the chamber was progressively less contaminated, while after closure of the magma chamber cumulates crystallised from magma that was progressively more contaminated. Contamination was probably ultimately related to the gradual assimilation of wall-rock xenoliths, but the relationships can suggest the lateral (northward) and upward emplacement of compositionally- and isotopically-zoned magma during a major (and final?) replenishment event in a large magma chamber at a slightly deeper structural level to the south. The abundance of country-rock xenoliths enclosed in UZ cumulates suggests that the xenoliths had a positive buoyancy, and assimilation probably mainly took place at the roof of the chamber.

5.2 The Rognsund Intrusion

The modally- and texturally-layered gabbroic rocks exposed on the coast in the Hakkstabben area of Seiland appear to belong to a single intrusion, the Rognsund Intrusion (RI), that occupies ~50km2. Layering in this intrusion generally dips moderately steeply towards a synformal axis beneath Rognsund. The RI post-dates the adjacent strongly-foliated Oldervik Metagabbro, and is cut by hornblende gabbro pegmatites, metamorphosed basaltic, ankaramitic and picritic dykes (forming quite dense swarms in certain areas), apatite-magnetite hornblende pyroxenite dykes, and syenite and nepheline syenite pegmatites. Magmatic textures in parts of the RI are overprinted by a metamorphic foliation that generally is coincident with the primary igneous layering. The RI is similar petrographically and in other respects to the Melkvann Gabbro and the Kvalfjord Gabbro that form the principal host rocks to the Melkvann and Kvalfjord Ultramafic Complexes. The crystallisation of the Melkvann Gabbro and the Kvalfjord Gabbro has been dated by Sm-Nd mineral isochrons to 559±36Ma (Snow 1986) and 612±33Ma (Daly *et al.* 1991) respectively. The RI is presumed to be of similar age.

The contact-metamorphic aureole. The effects of contact metamorphism extend >250m into the semipelitic and psammitic country rocks forming the floor to the RI.

The outer part of the aureole is characterised by the occurrence of orthopyroxene, garnet, cordierite, hercynitic spinel, corundum and rutile in rocks of appropriate composition. Two generations of folds that predated contact metamorphism are preserved in the metasediments. Amphibolitised mafic dykes in the outer aureole are recrystallised along their margins to pyroxene granulite.

The inner part of the aureole is composed of massive, coarse-grained, granitic to granodioritic rocks that contain angular to rounded inclusions of calc-silicate rocks, quartzite, Al-rich metasediment, and mafic dykes. These breccias are believed to have formed by disruption of the banded metasediments during extensive partial melting.

The internal structure. The RI on Hakkstabben contains a 800-950m thick sequence of cumulates that has been subdivided into 4 zones on mineralogical and textural grounds.

The 0-200m thick Contaminated Zone occurs along parts of the base of the Layered Series and consists of banded, rather strongly metamorphosed, olivine-free gabbronorite that encloses abundant metasedimentary xenoliths. A fine-grained facies along parts of the contact with the country rocks has been interpreted as a chill, and has the composition of an alkali olivine basalt.

The Basal Zone is up to ~200m thick and consists mainly of olivine gabbro, but olivine- and clinopyroxene- rich layers are present in places. Discontinuous, concordant, comb-textured dykes of coarse-grained hornblende gabbro occur at a particular horizon in the Basal Zone.

The Crescumulate Zone is distinguished on the basis of extremely coarse-grained olivine gabbroic cumulates with well-developed modal and textural layering, and the sporadic occurrence of layers of olivine or clinopyroxene-olivine crescumulate in which individual crystals are elongated almost at 90 degrees to layer boundaries.

The Cumulate Zone is >400m thick and is characterised by modally-layered olivine gabbros containing cumulus Fe-Ti oxides. Olivine in this zone is extensively oxidised to hypersthene-oxide symplectites.

The principal minerals show continuous but limited changes in composition through the Layered Series: Plagioclase varies from An_{84} at the base of the BZ to An_{65} at the limit of exposures in the Cumulate Zone; Olivine varies from Fo_{74} to $<Fo_{65}$ and Ca-rich pyroxene varies form $Ca_{47}Mg_{44}Fe_{9}$ to $Ca_{49}Mg_{35}Fe_{16}$. The cumulus Ca-rich pyroxene is rich in Al_2O_3 (4-7wt%) and commonly contains exsolved hercynitic spinel. Apart from the Contaminated Zone, *primary* Ca-poor pyroxene does not occur in the Rognsund Cumulates.

Petrogenesis. The assemblage and compositions of the cumulus minerals in the RI as well as the composition of the chill suggest crystallisation from an alkali olivine basalt parental magma. The early appearance of cumulus Fe-Ti oxides (when plagioclase of $\sim An_{81}$ was crystallising) suggests that the magma was relatively oxidised. There is no evidence in the exposed part of the Layered Series for replenishment of the magma chamber. Minor stratigraphic unconformities in the layering suggest active magma convection, while crescumulate layers containing meter-long skeletal olivines attest to periods when magma at the floor of the chamber was stagnant.

5.3 The Lille Kufjord Intrusion

The Lille Kufjord Intrusion (LKI) has an elongated outcrop, 6 km long and a maximum width of 1.6 km on the Northwest shore of Store Kufjord. It occupies a total area of about 6.5 km^2 and is an order of magnitude smaller than the layered mafic plutons of the Thulean Province, such as the Skærgaard Intrusion and the Rum Intrusion, Scotland, both with outcrop areas of about 50 km^2. The LKI appears to be one of the youngest of the suite of mafic plutons which constitute a major part of the SIP. An extremely fresh gabbronorite from the Upper Zone of the cumulate sequence in the Lille Kufjord Intrusion has yielded a Sm-Nd internal isochron age of $488 \pm 57 (2\sigma)$ Ma which is interpreted as the age of crystallisation (Daly *et al.* 1991).

Magmatic events which post-dated the crystallisation of the Lille Kufjord Intrusion are represented by dykes of granitic pegmatite, blastoporphyritic amphibolite and syenite pegmatite, emplaced in that order, which cut both the intrusion and the rocks of the envelope. In addition, a single dyke of nepheline syenite pegmatite has been recorded within the Lille Kufjord Intrusion. The amphibolites are members of a regionally-developed swarm of metamorphosed picrite/ankaramite - alkali olivine basalt dykes (Robins & Takla 1979) that also cut the nearby Rognsund Intrusion (Robins 1982) as well as the Melkvann Ultramafic Complex (Bennett *et al.* 1986).

Syenite pegmatites emplaced into the Lille Kufjord Intrusion are associated with narrow metasomatic aureoles. In the envelope, however, there are several zones in which the paragneisses have been transformed into alkali feldspar-ægirine augite-sphene-apatite fenites in connection with the intrusion of thin dykes of carbonatite. The most extensive of these zones appears to parallel the eastern contact of the Lille Kufjord Intrusion and extends northward from Skjåvikvatnet almost to the coast of Store Kufjord, a distance of about 1km. Further occurrences of fenite are found close to and subparallel with the south-west contact of the Lille Kufjord Intrusion on Store Kufjordnes. Fenitization in these zones overprinted fabrics related to the second generation of folds in the paragneiss, as well as contact-metamorphic mineral assemblages.

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

The contact-metamorphic aureole. The paragneisses in the contact metamorphic aureole show evidence of a complex structural evolution. At least two generations of folds affected the lithological banding prior to the emplacement of the Lille Kufjord Intrusion. Both generations of early folds are tight to isoclinal, similar folds associated with axial-planar foliations. Post-D1 mafic dykes (amphibolite) are common in the paragneisses and have either been folded by the younger generation of structures or undergone boudinage during their development, or both. Distant from the contact of the LKI, pelites and semipelites contain varying amounts of almandine garnet, biotite and sillimanite in addition to quartz, K-feldspar and plagioclase, indicating metamorphism in the upper part of the almandine amphibolite facies. Within about 400 m of the contact of the LKI biotite is less abundant and appears to have grown at the expense of distinctive contact-metamorphic assemblages including garnet, sillimanite, cordierite, hercynitic spinel and rutile. The less-aluminous metasandstones contain garnet, hypersthene, biotite and, less commonly, hercynitic spinel, in addition to quartz and feldspars. Hercynitic spinel is generally enclosed within garnet and sillimanite, suggesting that spinel and quartz coexisted at the highest temperatures attained during contact metamorphism (>770°C, Holdaway & Lee 1977, Vielzeuf 1983) and that the principal mineral assemblages developed as temperatures in the aureole waned. The compositions of coexisting garnet (Mg# = 50.8) and cordierite (Mg# = 88.6) suggest equilibration during cooling of the aureole rocks (to temperatures of 650-700°C) at a pressure between 5.4 and 8.2 kb, depending on P_{H2O} (Martignole & Sisi 1981, Aranovich & Podlesskii 1983). A lithostatic pressure in the upper part of this range (corresponding to P_{H2O} near to P_{total}) is considered unrealistic. Conditions corresponding to the highest pressures indicated by the garnet-cordierite thermobarometer would place the equilibrium in the stability field for kyanite as determined by Holdaway (1971) rather than that for sillimanite. Furthermore, the common occurrence of graphite in the inner part of the Lille Kufjord aureole indicates that P_{H2O} was substantially less than Ptotal.

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

Granitic neosomes are sporadically developed in metasandstones and metapelites throughout the contact-metamorphic aureole and may crosscut both the lithological banding in the paragneisses and the recrystallised amphibolites they enclose. In a zone up to about 15 m wide along the contact of the LKI the paragneisses are, however, distinctly migmatitic. Here, lithological banding in the paragneisses is less pronounced than elsewhere and a granodioritic neosome is abundant. Rheomorphic breccias are developed in places in this zone. They consist of blocks and slabs of paragneiss and mafic hornfels enclosed in massive or banded granodiorite and appear to have resulted from partial melting to a degree sufficient for disruption of the aureole rocks. In places, rocks in the migmatitic zone are characterised by ellipsoidal segregations, typically a few cm long, consisting of granoblastic plagioclase (confirmed by electron microprobe analysis) intergrown with hercynitic spinel and lesser amounts of corundum. These lenticular bodies generally reside in a quartzo-feldspathic matrix and in places are partly replaced by garnet. Their evolution is obscure but they appear to have developed within semipelitic protoliths, possibly by the high-temperature breakdown of garnet in the presence of anatectic melt. Although only a minor component, the occurrence of the aluminous lenticles in the innermost part of the contact-metamorphic aureole has important implications since identical bodies are exceedingly common as xenoliths throughout the Layered Series of the Lille Kufjord Intrusion. The mineralogical identity of the segregations in the aureole and xenoliths in the Lille Kufjord Intrusion appears to be evidence for significant assimilation of country rocks during the emplacement and crystallisation of the intrusion. The isotopic composition of a sample from the UZ of the intrusion (ε_{Nd} = -1.1, Sr_0 = 0.70549) suggests assimilation of 2-14% of wall-rock material (Aitcheson & Forrest 1994).

The internal structure. The rocks of the Lille Kufjord Intrusion can be subdivided into two petrographically, structurally and genetically different series:

1. The Marginal Series (MS) is up to 100m wide and consists principally of medium-grained to pegmatitic gabbronorites (±olivine) that crystallised on the steep walls of the magma chamber;
2. The Layered Series (LS) is more than 1400m-thick and consists of a variety of cumulates which crystallised on the floor of the magma chamber.

The outermost 2-3m of the MS consists of garnetiferous quartz gabbronorite which has a transitional contact with the migmatites in the inner part of the contact-metamorphic aureole; no fine-grained rocks representing chilled magma occur along the margins of the intrusion. The MS is composed of modally- and texturally-layered gabbronorite which contains sporadic olivine as well as pockets and bands of pegmatitic magnetite gabbronorite. Layering is generally subparallel with the external contact of the intrusion and may be either tabular, undulating or corrugated. Pegmatitic bands in the MS are conspicuously asymmetrical in that they are enriched in

Table 4. Summary of mineral compositions in the Lille Kufjord Intrusion.

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

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

plagioclase towards the exterior and in pyroxene towards the interior part of the Series. Some pockets of gabbronorite pegmatite show feldspar-rich margins and cores of either coarse-grained granitoid or paragneiss.

The layering in the Layered Series is discordant with that in the MS and in the SE half of the intrusion it defines a gentle, symmetrical and upright syncline which is interpreted to be a result of subsidence concurrent with formation of cumulates on the floor of the magma chamber. The LS can be subdivided into a 1130 m-thick Lower Zone consisting of feldspathic peridotite, olivine clinopyroxenite and olivine gabbro, i.e. cumulates in which cumulus olivine is ubiquitous and Ca-poor pyroxene has exclusively postcumulus status, and a 250m-thick Upper Zone characterised by more evolved, gabbronoritic cumulates containing cumulus Ca-poor pyroxene. The boundary between the Lower and Upper Zones has been mapped at the base of the stratigraphically-lowest cumulates containing cumulus orthopyroxene. For convenience of description the Lower Zone has been further subdivided into two subzones (LZa and LZb). The uppermost subzone (LZb) is c. 750m thick and consists almost exclusively of modally-layered olivine gabbro. In contrast, the 380 m-thick LZa contains a variety of distinctive types of cumulate (Fig. 3), including layers of feldspathic peridotite (olivine cumulate, oC), olivine clinopyroxenite (diopside-olivine cumulate, doC) and rare troctolite (plagioclase-olivine cumulate, poC), in addition to olivine gabbro (plagioclase-diopside-olivine cumulate, pdoC). The boundary between the subzones is placed at the top of the stratigraphically-uppermost peridotite layer. Repetitions of a single layer sequence (oC-doC-pdoC) builds up most of LZa and indicates the repeated operation of a singular cyclic process during this interval in the life of the magma chamber. The variations on the most common layer sequence which constitute a smaller number of macrorhythmic units in LZa nevertheless suggest the recurrence of a number of other phenomena during crystallisation.

Petrogenesis. The modal composition, mineral chemistry and textural relationships of LZ cumulates in the Lille Kufjord Intrusion are all consistent with a subalkaline olivine basalt parental magma. There is textural evidence in the cumulates for a peritectic at which cumulus olivine reacted with differentiated pore melts to produce orthopyroxene and this is mirrored in the stratigraphy of the Layered Series by the entry of cumulus orthopyroxene and disappearance of cumulus olivine at the Lower Zone/Upper Zone boundary. Intercumulus hornblende appears in virtually all of the LZ cumulates and is abundant in some varieties. Its presence indicates that the water content of parental magmas was sufficient to stabilise hornblende after moderate degrees of intercumulus crystallisation. The composition of the most magnesian olivine (Fo82, in oC) suggests that the magmas introduced into the Lille Kufjord magma chamber were not primary, but had undergone previous fractional crystallisation (and contamination?) during ascent from their source region.

The Marginal Series of the LKI appears to have crystallised from relatively-differentiated, basalt magma, contaminated by assimilation of varying amounts of country-rock paragneiss, that was cooling as it flowed down the margins of the magma chamber.

The most common layer sequences observed (oC-doC-pdoC, see above) suggest that magmas which repeatedly invaded the Lille Kufjord chamber during the crystallisation of LZa had olivine as their first liquidus phase. These magmas subsequently evolved through compositional space onto and along an olivine-augite cotectic as they cooled and crystallised. However, the magma which cooled in the chamber during most of the time represented by the accumulation of LZa crystallised along a three-phase (plagioclase-augite-olivine) cotectic. Magma crystallising exclusively along this cotectic was present in the magma chamber during the formation of LZb. During this interval of time the magma chamber appears to have evolved as a closed system and differentiation eventually resulted in the cessation of olivine crystallisation and the stabilisation of orthopyroxene on the liquidus, marked in the cumulate stratigraphy by the LZ/UZ boundary. The composition of olivine just prior to its cumulus termination was about Fo_{70}, more magnesian than in the Skaergaard Intrusion where the olivine gap is Fo_{52-36} (Wager & Brown 1968). This difference between the two intrusions suggests a higher silica activity in the Lille Kufjord magma. During the formation of the UZ cumulates the magma chamber appears to have continued to cool without frequent or major perturbation due to the inflow of magma. The recurrence of rare olivine gabbro layers within the gabbronorite UZ cumulates does suggest, however, the occasional addition of magma which caused crystallisation to revert to an earlier stage in the general differentiation trend.

The oldest exposed cumulates, at the base of LZa, contain the most iron-rich olivine (Fo_{71-66}) found so far in the Layered Series (Fig. 3). In the lowest 150 m of the LZa sequence olivine exhibits an irregular, upward trend to more magnesian compositions as measured in equivalent cumulate types. This pattern suggests that the initial formation of LZa resulted from fractional crystallisation of relatively differentiated magmas. The magma introduced into the chamber during the deposition of the lower part of LZa appears, however, to have been sufficiently voluminous to more than offset fractional crystallisation. Thus, the resident magma gradually became less differentiated until a quasi steady state was attained in the magma chamber, the rate of magma inflow approximately balancing the effects of fractional crystallisation. The cumulate sequence forming LZa is postulated as having crystallised in a compositionally-zoned magma chamber. The zonation was a consequence of the periodic emplacement of hot, dense magma which underflowed the more-voluminous and more-differentiated magma already residing in the chamber. As the new magma fountained into the chamber it spread into either a discrete basal layer or formed a series of independently-convecting layers of varying composition, temperature and density. The subsequent evolution of the magma above the floor of the chamber is envisaged as a complex interplay of thermal convection, fractional crystallisation, two-phase convection and compositional convection, all consequences of cooling into the overlying magma. As cooling progressed, the configuration of the convection changed by slow migration and abrupt disappearance of double-diffusive interfaces. Cumulates were, however, generated exclusively from the lowermost and hottest convecting layer.

The formation of macrorhythmic units of the most common type is proposed to have taken place by the following sequence of processes. Initially, the lowermost magma layer was cooling rapidly along its diffusive interface with overlying cooler magma, leading to the formation of a thin boundary region in which olivine crystals nucleated and grew. Instability in this denser region resulted in two-phase convection (Morse 1986, Marsh 1988). Plumes of magma containing suspended olivine continually sank to the floor of the chamber where their velocity was checked and, as the crystal suspensions spread out, crystals settled onto the depositional interface. The less-dense, residual magma was returned and mixed into the main body of the layer. At this early stage, the large difference in temperature across the sharp upper interface of the basal magma layer led to a relatively high degree of undercooling beneath the upper diffusive interface. This resulted in rapid crystal growth relative to the rate of crystal nucleation and the olivines deposited were relatively large. As the basal magma layer approached thermal equilibrium with the overlying magma the degree of undercooling diminished and smaller olivines were transported in and deposited from the descending plumes.

Differentiation of the basal layer continued until the magma attained a composition close to the olivine-clinopyroxene cotectic. At this stage some plumes transported only olivine to the floor while others which contained magma which had experienced more cooling in the upper boundary region carried both olivine and clinopyroxene. The latter experienced sorting according to their size and density in the boundary region, during transport in plumes and during deposition on the floor. The origin of the modal layering in doC macrolayers in LZa is thus envisaged as a consequence of the mode of cooling and the nature of the convection which took place in the basal layer. Eventually the magma layer evolved towards a composition close to the plagioclase-clinopyroxene-olivine cotectic as its temperature (and density) decreased. Plagioclase began to crystallise in the upper, coolest part of the thermal boundary region while exclusively olivine and pyroxene were crystallising in its lower, hotter part. Plumes forming at this stage carried a mixture of the three phases in non-cotectic proportions, the heads of the plumes concentrating olivine and pyroxene while the tails contained all three phases suspended in slightly more-differentiated liquid. Further sorting could take place during the downward and lateral movement of plumes and possibly while crystals sank from suspension onto the floor of the chamber. This phase in the evolution of the basal layer is suggested by the modally-layered olivine melagabbroic cumulates which generally form the basal parts of pdoC macrolayers. Finally the basal magma layer attained a composition on the three-phase cotectic. Crystallisation along the diffusive boundary continued to generate crystal-bearing plumes in which mineral phases were crudely sorted according to their sizes and densities. On average, however, the minerals were now deposited in cotectic proportions.

The evolutionary cycle leading to a macrorhythmic unit of the ideal type could be terminated prematurely at any stage by emplacement of a new batch of high-temperature magma. A new batch of magma may have been emplaced while the basal magma layer remaining from a previous influx was still crystallising olivine alone. The new basal liquid layer(s) could in this case have mixed with the succeeding layer at an early stage in its differentiation, the crystalline products being olivine cumulates both before and after homogenisation. Mixing events of this nature may not be detectable in the resulting sequence of uniform cumulates, though the emplacement of the new batch of magma may be marked by a regression in the composition of olivine (e.g. Irvine 1980). Influx of magma at a somewhat later stage, when the basal layer had differentiated to saturation in clinopyroxene, could elevate this liquid layer. If the temporary floor of the chamber exhibited a sufficiently persistent slope, then the more differentiated liquid could spread over a higher part of the cumulate-magma interface (Irvine *et al.* 1983, Robins *et al.* 1987). On the part of the floor overrun by the elevated liquid layer a macrorhythmic unit could be initiated by precipitation of a macrolayer of clinopyroxene-olivine cumulate. As noted above, units of this type are represented in LZa. They may have been generated by this combination of repeated influx, differentiation and a sloping floor. A high degree of mixing during emplacement and fractional crystallisation of new magma is a possible mechanism for the origin of the uncommon macrorythmic units consisting only of macrolayers of oC and pdoC. It seems unlikely, however, that cumulates on the floor or walls of the magma chamber could be assimilated in sufficient volume to alter the sequence of crystallisation to the extent required. An alternative and preferred hypothesis appeals to withdrawal of magma from the base of the chamber. This process may have resulted in subsidence of the compositionally-stratified magma column, bringing less-dense, more-differentiated magma to the floor.

6. Ultramafic complexes

There are several major ultramafic complexes and many smaller ultramafic intrusions in the SIP (see Table 3). With the exception of the Reinfjord U.C., they form a coherent group with so many features in common that they can be regarded as cogenetic (but they need not be all of exactly the same age). All of the U.C.s are emplaced discordantly into deformed olivine gabbro plutons, though in places the ultramafic rocks crosscut the margins of the gabbros and come into contact with other rocks, including metasediments and older gabbroic intrusions. The main rock type is coarse-grained olivine clinopyroxenite containing variable amounts of plagioclase and hornblende. This is accompanied by lesser amounts of wehrlite, dunite, pyroxene-hornblende peridotite and other amphibole-rich ultramafic rocks, olivine melagabbro and hornblende gabbro. Modal or textural layering is generally absent, but does occur in certain late-stage differentiated dykes.

The ultramafic complexes are cut by a variety of later dykes. Mafic dykes with chilled margins form dense swarms in some areas. The mafic dykes largely predated the emplacement of apatite-hornblende pyroxenite dykes, syenite and nepheline syenite pegmatites, as well as rare, thin carbonatite dykes. Many of these later intrusions are foliated and some of the alkaline pegmatites are mylonitised, but the ultramafic and other rocks in the U.C.s are virtually undeformed.

6.1 The Melkvann Ultramafic Complex

The Melkvann U.C. covers an area of ~100km^2 in the southern part of the island of Seiland (Fig. 1) and is by far the largest of the ultramafic complexes. It was emplaced into a modally-layered olivine gabbro that generally exhibits a layer-parallel metamorphic foliation. The gabbro intrusion is preserved in places along the margin of the U.C. and as large enclaves within it. The crystallisation of the Melkvann Gabbro has been dated by a Sm-Nd mineral isochron to 559±36Ma (Snow 1986).

The contacts of the U.C. are discordant, near vertical or inwardly-dipping. In places the contact with the country-rocks is transitional, with sheeted ultramafic or hornblende-olivine melagabbro dykes increasing in frequency into the complex. Two zones can be recognised in the complex:

- A Roof Zone, particularly well developed on Steinfjell in the NW corner of the complex and in topographically higher areas near the western margin;
- A Central Zone generally occupying topographic lows, e.g. around Holmevann and Nordre Steinvatnet.

In the Central Zone olivine clinopyroxenite is the dominant rock type. Locally it grades into wehrlite (and less commonly dunite), or feldspathic olivine-hornblende clinopyroxenite. The latter is most common near the margins of the complex where it often contains xenoliths of olivine gabbro and, less commonly, wehrlite and olivine clinopyroxenite. The olivine clinopyroxenite is cut in places by dykes and irregular bodies of wehrlite and dunite containing poikilitic clinopyroxene. Some of these intrusions contain aligned xenoliths of olivine clinopyroxenite and a crude banding, suggesting flow in a viscous crystal mush. In the olivine clinopyroxenite adjacent to the wehrlite intrusions there are commonly patches of wehrlite and dunite that appear to have formed by replacement. The Central Zone contains a large number of late-stage dykes, composed of coarse-grained ultramafic rocks in which hornblende may be a prominent mineral, that form as much as 50% of individual areas.

The Roof Zone is characterised by olivine gabbro enclaves, that are both intruded and separated by ultramafic rocks or olivine melagabbro. The enclaves generally have a pronounced modal layering, but structures such as modal grading, minor unconformities

Table 5. Compositions of the main minerals in the Melkvann mantle-derived xenoliths*

Xenolith type	Olivine Fo	Orthopyroxene Wo En Fs	Clinopyroxene Wo En Fs	Spinel	Accessory minerals
Type I	87-91	0.2-0.7 84-90 9-16 Al_2O_3 0.4-3.9 Cr_2O_3 0.2-3.9	44-49 47-50 4-6 Al_2O_3 2.0-4.6 Cr_2O_3 0.8-2.5	Variable composition Al_2O_3 12-64 Cr_2O_3 12-58	Na-rich plagioclase pargasitic amphibole phlogopite
Type II	74-81		47-51 40-44 9 Al_2O_3 5.0-8.0 Cr_2O_3 0.1-0.8	Al-rich Al_2O_3 55-62 Cr_2O_3 2-5	kaersutite phlogopite orthopyroxene Fe-Ti oxides sulphides

* Al_2O_3 & Cr_2O_3 reported in wt.%

and slump structures are rare. A metamorphic foliation is generally present parallel to the modal layering and in some areas it is intense and the gabbroic rocks have a gneissic appearance. The orientation of the modal layering in the enclaves, regardless of their size and separation, forms a systematic pattern. This shows that the enclaves were never xenoliths and rafts of gabbro that became detached from the roof of a magma chamber. They must represent blocks of the host intrusion that became isolated by the repeated emplacement of magma into dykes and sheets that gradually fragmented the olivine gabbro. The evolution of the roof zones is complex and there are many bewildering structural and relationships. Detailed work in the Steinfjell area, where exposure is complete, has revealed the following sequence of events:

1. Passive replacement of olivine gabbro by olivine melagabbro;
2. Emplacement of olivine clinopyroxenite dykes (in places with wehrlite or dunite along their margins) accompanied by dissolution of the gabbroic wall rocks, producing highly irregular contacts and enclaves of olivine gabbro. Adjacent to ultramafic dykes the olivine gabbro is locally altered to coarse-grained troctolite;
3. Partial melting of olivine gabbro contemporaneous with 2, leading to the emplacement of dykes of olivine gabbro pegmatite and igneous breccias with blocks of gabbroic and ultramafic rocks enclosed in an olivine leucogabbro matrix;
4. Emplacement of dilational dykes of wehrlite, olivine clinopyroxenite and olivine-hornblende clinopyroxenite (early) or clinopyroxene-hornblende peridotite, olivine-hornblende clinopyroxenite, olivine-clinopyroxene hornblendite and hornblende melagabbro (late).
5. Emplacement of mafic dykes (with chilled margins) and alkaline pegmatites.

In a ENE-WSW zone extending from Holmevann to Nik´kavarri some dilational olivine clinopyroxenite or amphibole-bearing wehrlite dykes, up to ~20m wide and >1km long, contain abundant mantle-derived xenoliths up to 60cm in diameter. The xenoliths can be subdivided into several suites: Type I spinel lherzolite, harzburgite, dunite and wehrlite; Type II olivine websterite, olivine clinopyroxenite, wehrlite and dunite; Composite type I/typeII xenoliths (see Table 5 for the composition of the main minerals).

The type I xenoliths are commonly lithologically banded and strongly foliated. They exhibit a variety of fabric types from laminated, disrupted, porphyroclastic to granuloblastic. Porphyroclastic xenoliths are dominant at Holmevann and ~50% of xenoliths at Nik´kavarri are mosaic porphyroclastic. Composite xenoliths consist of type I xenoliths cut by dykes (1-4cm wide) or veins (<1cm) of hornblende clinopyroxenite containing small amounts of spinel, olivine and plagioclase. The dykes and veins are almost always undeformed and cut the foliation in the type I hosts, implying that they post-dated plastic deformation in the mantle. The type I xenoliths are believed to have been derived from the lithospheric mantle at a depth of 25-55km (8-18kb), above the site of magma generation and were transported upward at velocities of 2-3km/hour. The type II xenoliths probably represent mantle cumulates that crystallised from basaltic magmas.

Some of the late-stage amphibole-rich dykes in the Melkvann U.C. are up to ~20m wide, can be traced laterally for hundreds of meters, and exhibit mineral lamination and modal and phase layering within thin marginal series. In one of these dykes there are repetitions of sequences of olivine, clinopyroxene-olivine and plagioclase-clinopyroxene-olivine cumulates, all of which contain hornblende as an important postcumulus mineral.

Petrogenesis. A variety of processes were operative during the evolution of the ultramafic complexes, including fractional crystallisation, assimilation of olivine gabbro, partial melting and remobilisation of olivine gabbro, and metasomatism of both olivine gabbro and ultramafic rocks (probably during the infiltration of magma through pores).

The parental magmas were picrite, ankaramite and olivine basalt, emplaced in order of increasing MgO to produce the regressive intrusive sequence of olivine gabbro, olivine clinopyroxenite, wehrlite/dunite. The absence of magmatic orthopyroxene in the majority of the complexes and the aluminous clinopyroxene show that the magmas were of alkaline affinity. The principal rock types were generated by fractional crystallisation. Olivine clinopyroxenite resulted from the cotectic crystallisation of olivine and clinopyroxene. Wehrlite and dunite represent the crystallisation of more magnesian magmas with only olivine (and in some instances spinel) on the liquidus.

The presence of mantle xenoliths in some of the later ultramafic dykes shows that the magmas were emplaced directly from the upper mantle, and were not stored in a lower-crustal chamber. The isotopic compositions of ultramafic rocks from the Melkvann and Kvalfjord complexes ($\varepsilon Nd = +4.5\text{-}5.8$, $Sr_0 = 0.7029\text{-}0.7036$ at 560-540Ma) is also similar to that of the Type I mantle xenoliths ($\varepsilon Nd = +4.3\text{-}7.5$, $Sr_0 = 0.7030\text{-}0.7055$ at 540Ma). The host olivine gabbros have isotopic compositions in the same range ($\varepsilon Nd = +4.2\text{-}5.5$, $Sr_0 = 0.7028\text{-}0.7039$ at 612-559Ma). The initial isotopic ratios suggest that neither the olivine gabbros nor the ultramafic rocks contain a significant crustal component.

The olivines in the ultramafic rocks are not particularly magnesian, even in wehrlite and dunite. Olivine in the dykes containing mantle xenoliths is $\sim Fo_{76}$. This suggests that the parental magmas were generated by melting of fertile mantle rocks with low MgO/MgO+FeO compared to a MORB-type source. The isotopic compositions nevertheless shows that the source had low time-integrated Rb/Sr and Sm/Nd ratios.

The youngest of the ultramafic rocks, the amphibole-rich dykes, appear to have crystallised from magmas that were more evolved, and more hydrous, than those emplaced earlier. *In situ* fractional crystallisation took place in some of the dykes as reflected by the variations in olivine and pyroxene compositions ($Fo_{78\text{-}71}$, $Ca_{48\text{-}49}Mg_{42\text{-}39}Fe_{9\text{-}13}$).

7. Mafic dykes

Mafic dykes are abundant in the SIP. They are generally thin and dykes >2m in thickness are rare. Their frequency varies considerably. In some areas, generally within mafic or ultramafic plutons, they are extremely common and can constitute up to ~60% of the rock volume. Although linear dyke swarms are present locally, there is no predominant dyke trend within the SIP. Dyke magmas appear to have invaded pre-existing fracture systems, and because of this their courses are highly irregular.

The degree of metamorphic recrystallisation varies greatly. Many dykes are completely recrystallised granular or foliated amphibolites, but blastoporphyritic varieties that contain phenocrysts of plagioclase, olivine or Ca-rich pyroxene are not uncommon. Phenocrysts have been concentrated towards the cores of some dykes during magma flow. Individual picritic dykes in the Hakkstabben area of Seiland contain small lherzolite xenoliths (and probably xenocrysts) of mantle origin, and these provide a genetic link with the wider ultramafic xenolithic dykes within the Melkvann U.C. Mafic dykes occasionally form composite intrusions with granitoid and syenitic rocks. Some of these show structural evidence for the coexistence of two magmas of contrasting composition.

Mafic dykes appear to have been emplaced at widely different times during the magmatic history of the SIP. This can be demonstrated in the contact-metamorphic aureoles adjacent to individual intrusions, where earlier mafic dykes have been recrystallised during contact metamorphism and in places disrupted during anatexis of the aureole rocks, while the intrusion and its aureole are cut by younger mafic dykes. The maximum relative ages of individual dykes is given by the geological setting, for instance mafic dykes emplaced into the late-stage alkaline rocks are the youngest that can be distinguished in the SIP on the basis of field relations.

The mafic dykes from Seiland and Stjernøya analysed by Robins & Takla (1979) have alkali olivine basalt affinities (MgO = 6.9-19.8wt%) and a mean composition in the picrite range. The main compositional variations can be explained by olivine and clinopyroxene control. In terms of trace-element concentrations the dykes equate with with-plate basaltic suites, and the magmas were interpreted as having been generated by relatively small degrees of partial melting of an inhomogeneous garnet lherzolite at a depth >70km.

Reginiussen *et al.* (1995) recognised that dykes in the Øksfjord-Langfjord region represented at least 5 different generations. Major- and trace-element analyses (mainly of «post-kinematic» dykes) showed that the dykes were mainly within-plate, alkali olivine basalts derived from a garnet-bearing source. The youngest dykes that were recognised are restricted to the Tappeluft area and intimately associated with syenite pegmatites. They are alkaline lamprophyres that may have originated by «wet» melting.

Recent studies by Reginiussen (in press) of mafic dykes from Sørøya (mainly from the Hasvik-Breivikbotn area, and excluding the most metamorphosed varieties) show that they also have within-plate, alkali olivine basalt affinities. The earliest dykes within the Hasvik Gabbronorite are, however, foliated amphibolites (some of which contain garnet) and appear to be mainly quartz- to olivine-normative tholeiites (Gardner 1980). The later, post-shearing, dykes are texturally less-metamorphosed alkali olivine basalts.

The preliminary conclusion reached on the basis of the studies carried out so far on the mafic dykes is that the majority are related to alkali olivine basalt magmatic activity, and that this activity seems to have persisted for a considerable time in the SIP.

8. The alkaline rocks

8.1 The Lillebukt Alkaline Complex

The Lillebukt Alkaline Complex occupies a N-S elongated area of about 13 km^2 (Heier 1961). The main rock types, hornblende clinopyroxenite, laminated alkali syenite, nepheline syenite and carbonatite, are organised in a crudely concentric pattern (see enclosed map). Carbonatite forms the core of the complex and is surrounded by, and intrudes, either hornblende clinopyroxenite (in the northern part of the complex) or nepheline syenite and minor alkali syenite (in the southern part of the complex). The syenitic rocks were emplaced in the sequence: Perthositic syenite (oldest), laminated alkali syenite, nepheline syenite. Age relations between these and the hornblende clinopyroxenite have not been established as they are not in mutual contact. The carbonatite was post-dated by alkali syenite and nepheline syenite pegmatites as well as rare dykes of granular alkali syenite and mafic dykes. The dykes of granular syenite appear to have been emplaced prior to the pegmatites while mafic dykes both pre- and post-dated carbonatite intrusion, some having been intruded after the pegmatites. The metagabbroic host rocks were locally intensely metasomatised during the emplacement of nepheline syenite, hornblende clinopyroxenite and carbonatite and the resulting fenites are in each case mineralogically distinctive.

Strong, inhomogeneous deformation of the Lillebukt Alkaline Complex is expressed in a number of ways: The alkali syenites and nepheline syenites have a composite magmatic/metamorphic foliation in which alkali feldspars show a strong statistical orientation; A lit-par-lit unit consisting originally of sheets of nepheline syenite separated by fenitized metagabbro is now in the condition of a gneiss; The carbonatite is strongly banded and contains tectonic inclusions of its host rocks and later, crosscutting intrusions (commonly nepheline syenite pegmatite and mafic dykes); The banding in the carbonatite is disposed around mesoscopic folds of two generations (in places accompanied by axial planar biotite foliations), and appears in places to have resulted from the disintegration of xenoliths and tectonic inclusions; The complex is dissected by high-strain zones associated with overthrusting.

The hornblende clinopyroxenite generally shows little sign of strain and occurs around the northern and eastern margins of the complex as a 50-600 m wide and 11 km long swarm of subparallel, steeply-dipping, coarse-grained to pegmatitic dykes. Individual dykes are generally 50-100 cm wide and are separated by screens of fenite derived from the olivine gabbro host rocks. Fenite screens may form up to 40% of the volume of the zone. Multiple dykes more than 10 m wide have been noted in places in the swarm. The dykes lack marginal chilled zones and commonly are characterised by a comb structure defined by orientated clinopyroxene and hornblende crystals up to 50 cm long as well as highly-elongated and skeletal apatite crystals. Cores of dykes may be finer grained and in some cases are enriched in apatite and Fe-Ti oxides.

The hornblende clinopyroxenites are ultrabasic, under-saturated rocks containing Al_2O_3-rich salite, Ca-rich amphibole, apatite, ilmenomagnetite, ilmenite, hercynitic spinel and small amounts of sulphides. Feldspar and feldspathoids are absent. The fenites associated with the magmatic hornblende clinopyroxenite are granular, medium- to coarse grained, massive or banded rocks which also consist predominantly of salite and Ca-rich hornblende together with Fe-Ti oxides, apatite and accessory calcite.

The perthositic syenite forms a number of thick sheets in the southern part of the complex and are the oldest of the felsic intrusives. They are mineralogically and chemically distinct from the later alkali and nepheline syenite and are believed to significantly older than, and genetically unrelated to the rest of the alkaline complex.

The alkali syenites are miascitic, hypersolvus rocks characterised by laminated perthitic alkali feldspar, oligoclase, hornblende, Ca-rich pyroxene and accessory sphene and Fe-Ti oxides. They form thin sheets closely associated with, but cut by nepheline syenite. The latter is a coarse-grained rock type dominated by K-rich perthitic alkali feldspar and nepheline which occur together with limited amounts of biotite, hornblende, Ca-rich pyroxene (salite or ferrosalite), sodalite, calcite, sphene, Fe-Ti oxides, apatite, corundum and zircon. Two main mineralogical types have been recognised, one characterised by biotite and sphene, the other by hornblende and pyroxene. Despite statements to the contrary (Geis 1979), the nepheline syenites are magmatic rather than metasomatic rocks and appear to be related to the alkali syenites by fractional crystallisation, though other genetic models are possible.

The steeply-dipping sheets and lensoid intrusions of nepheline syenite are generally separated from carbonatite by a wide, moderately- to strongly-deformed zone consisting of gneissic nepheline syenite interleaved with fenitized mafic rocks together with more sheets of more homogeneous nepheline syenite and thin concordant carbonatite intrusions. This zone is tectonically truncated towards the eastern margin of the alkaline complex.

The calcite-carbonatites in the complex are inhomogeneous and contain on average 40 modal% strontian calcite. Biotite is the main mafic mineral, but in the vicinity of contacts with hornblende clinopyroxenite or fenitized mafic rocks, hornblende, sphene and Ca-rich pyroxene dominate over biotite. Nepheline and feldspar have an irregular distribution and are most common near contacts with, and xenoliths of nepheline syenite and tectonic inclusions of nepheline syenite pegmatite. Fe-Ti oxides form large clumps in places in the carbonatite but no Nb- or REE-minerals have yet been discovered. The mineralogical and chemical variations in the carbonatites are probably the result of a variety of processes, including reaction with and assimilation of host rocks during intrusion of fluid and reactive carbonatite magma, fractional crystallisation and accumulation of liquidus minerals and the purely mechanical incorporation of xenocrysts during deformation and plastic flow.

Narrow, deformed and metamorphosed mafic dykes cut all rock types in the Lillebukt Alkaline Complex with the exception of some nepheline syenite pegmatites. They are particularly common in parts of the Nabberen nepheline syenite where they form quite dense swarms (Ramsay & Sturt 1970, Robins & Takla 1979). One such swarm is well displayed in 3-dimensions in the walls of a spiral tunnel in the nepheline syenite mine (Ramsay & Sturt 1970). In both surface and underground exposures there is evidence for several generations of mafic dykes. Most mafic dykes emplaced in nepheline syenite are cut by nepheline syenite pegmatite, but some were intruded through nepheline syenite pegmatites and thus represent the youngest intrusives in the Lillebukt Alkaline Complex.

The Lillebukt Alkaline Complex was probably emplaced at a shallow crustal level in a subvolcanic environment as a pipe-like body containing a collapsed cylindrical block of country rocks within a carbonatite ring dyke. This conclusion is supported by the following observations:

- Hornblende clinopyroxenite forms a crudely cylindrical zone with an axis plunging northwards;
- Syenite/nepheline syenite sheets in the southern part of the complex terminate laterally at carbonatite dykes;
- Perthosite sheets are restricted to the southern part of the complex within marginal carbonatite dykes. They are older and not related to the other rocks of the complex;
- The metasomatised host rocks to perthosites, alkali syenites and nepheline syenites in the southern part of the complex were different from those north of the Nabberen body and are not found outside the complex.

8.2 The Breivikbotn Alkaline Complex

Alkaline rocks associated with carbonatite in the Breivikbotn area of Sørøya occur in a poorly-exposed, sill-like body up to 250 m wide and over 7 km long, emplaced in fenitized psammitic and semipelitic metasediments of the Klubben Formation (Sturt & Ramsay 1965). The metasediments and in particular the adjacent Breivikbotn Metagabbro and its marginal noritic and dioritic intrusions are cut by numerous pegmatitic or gneissic bodies of alkali syenite or nepheline syenite, but according to Sturt & Ramsay 1965 these are not seen in contact with the carbonatite-bearing complex.

The rocks associated with the carbonatite were emplaced in the sequence: Pyroxenite (oldest); malignite; nepheline syenite; alkali syenite. The pyroxenite consists of aegirine-augite, hastingsitic amphibole, sphene and plagioclase (An_{8-12}), together with accessory alkali feldspar, apatite, allanite, biotite, magnetite and pyrite. It probably is a metasomatically altered metagabbro.

The malignites are coarse grained, miascitic rocks consisting of alkali feldspar, sodic plagioclase, zeolites (after feldspar according to Sturt & Ramsay, op. cit., but recent observations by Asle Jonassen show that the zeolites replaced nepheline), aegirine-augite, hastingsitic amphibole, melanite (Ti-andradite) and calcite with sphene, apatite, allanite, pyrite, zircon, biotite, magnetite, ilmenite, analcite and pyrochlore as accessories. They are banded and foliated, the foliation being at least in part of tectonic origin since it is parallel to the axial surfaces of folds affecting mafic dykes emplaced into the melasyenite.

The alkali syenites cut the melasyenites and consist largely of alkali feldspar, zeolites, aegirine augite, amphibole, biotite and sphene together with the same accessories as in the melasyenites. In places, alkali feldspars are strongly laminated. If in these rocks zeolites are after nepheline, as suggested by the chemical compositions of the rocks, then they are altered *nepheline syenites*. All of the syenites were intruded by mafic dykes and subsequently deformed and foliated. Carbonatite dykes are common in the syenites and are generally concordant to their banding.

The calcite-carbonatites vary from breccias containing blocks of strongly-deformed metasediment, pyroxenite, syenite and mafic dyke material as well as alkali syenite (which elsewhere forms deformed dykes cutting both pyroxenite and syenite), to xenolith-free, generally banded sheets. The carbonatites are sövites and silicosövites with variable modal compositions. They contain calcite, aegirine-augite, amphibole, sphene, apatite, allanite and magnetite. Melanite and biotite are present in places. The carbonatite breccias are regarded as tectonically emplaced. Other carbonatite sheets that contain large euhedral sphene and apatite crystals are, however, in situ intrusions.

Although described by Sturt & Ramsay (1965) as the latest intrusive event in the complex, the primary emplacement of the carbonatites probably took place before the mafic and alkali syenite dykes. Indeed, Sturt *et al.* (1978) refer to an "aplitic" alkali syenite that cuts carbonatite. Due to the probable tectonic emplacement of the carbonatite breccias, inclusions must be regarded as unreliable indicators of relative age. This conclusion is supported by observations in the Lillebukt and Pollen Complexes.

Although not reported by Sturt & Ramsay (1965), nepheline syenite protomylonites are present in the Baarvik shore section through the carbonatite-bearing alkaline complex. They occur as rafts or boudins in carbonatite and also as screens together with fenites and appear to have developed from pegmatite dykes. At Haraldseng narrow nepheline syenite pegmatites cut across the banding of the malignites. They are themselves cut by amphibolite dykes and thin shear zones.

8.3 Alkali syenite and nepheline syenite pegmatites

Alkali syenite and nepheline syenite pegmatites have a wide distribution in the northern and eastern portions of the Seiland Province and can attain substantial dimensions. The Bekkarfjord Pegmatite Complex (Seiland), for instance, comprises a number of subparallel nepheline syenite pegmatites which extend for about 9km from Bekkarfjordnes, towards Hakkstabben, and is exposed over a relief of about 700m. Individual pegmatites in this swarm have widths of up to 100m. In some swarms, pegmatite dykes exhibit an *en echelon* pattern.

Syenite and nepheline syenite pegmatites commonly occur in the same or adjacent areas but only rarely can crosscutting relations be observed. In a few places nepheline syenite pegmatites can be shown to be younger than alkali syenite pegmatites, though age differences are likely to be small (see below). U-Pb dates from euhedral zircon from two pegmatites (at Store Kufjord and in the Lillebukt alkaline complex) does suggest, however, that pegmatite emplacement took place during an extended period of time, from 531 to 523Ma (Pedersen *et al.* 1989).

The nepheline syenite pegmatites are commonly zoned. Narrow wall zones of alkali syenite are present in several cases and consist of sodic alkali feldspar, biotite and Fe-Ti oxides with accessory apatite, zircon and hercynitic spinel. Dyke cores comprise sodic alkali feldspar, nepheline, biotite, Fe-Ti oxides, calcite, corundum, apatite, zircon and hercynitic spinel. Some dykes have a core of carbonatite pegmatite surrounded by a narrow zone consisting of subhedral to euhedral alkali feldspar crystals in places intergrown with large apatite prisms and separated by granular apatite or calcite (Robins 1972). In exceptional cases, biotite crystals up to 1 m across occur along the boundary between the apatite syenite zone and the carbonatite pegmatite core.

Like the carbonatite-bearing alkaline complexes, the pegmatites exhibit variable degrees of later (Caledonian) deformation. Many are reduced to protomylonites and some are transformed, either completely, or in particular zones, to mylonite. The restriction of deformation to the pegmatites and adjacent fenitized country rocks is clearly a consequence of pronounced ductility contrasts.

8.4 Petrogenesis of the alkaline rocks

Each of the alkaline complexes in the Seiland Province exhibit different associations of alkaline rocks. The malignites of the Breivikbotn Complex have no counterparts in the Lillebukt Complex, while the potassic nepheline syenites which characterise the Lillebukt Complex are reportedly not found in the Breivikbotn Complex (but see above). With the exception of pegmatites, syenites are absent from the Pollen Complex. Hornblende clinopyroxenite is apparently unique to the Lillebukt Complex, but similar rocks do occur as narrow dykes in other parts of the Seiland Province, for instance at Hakkstabben and around the head of Store Bekkarfjord.

Despite these differences, the alkaline rocks in all three complexes have a geochemical coherence. They are all miascitic and characterised by similar, high concentrations of Ba and Sr. The carbonatites are petrographically similar. In addition, the sequences of intrusion are comparable in all complexes. In view of these observations, a unified petrogenetic scheme seems reasonable.

The low Mg/Mg+Fe in all rocks in the alkaline complexes suggests crystallisation from low-temperature, differentiated magmas. The syenites and nepheline syenites of the Lillebukt Alkaline Complex exhibit slight positive Eu anomalies in their chondrite-normalised REE patterns. This, their high Sr concentrations and peraluminous compositions, suggests derivation without the intervention of prolonged plagioclase fractionation. A mantle-derived, carbonated nephelinite magma is therefore suggested as parental to the alkaline complexes. This magma is envisaged as having evolved by fractional crystallisation (of olivine, Ca-rich pyroxene, amphibole and nepheline?) until it encountered a solvus, when it exsolved an immiscible carbonatite magma. Further differentiation of the nephelinite, with the separation of pyroxene and nepheline, led to a low-temperature, Sr-rich phonolite magma. Fractional crystallisation of potassic alkali feldspar and nepheline (in some cases together with aegirine augite and melanite) from batches of phonolite emplaced into the alkaline complexes produced the nepheline syenites.

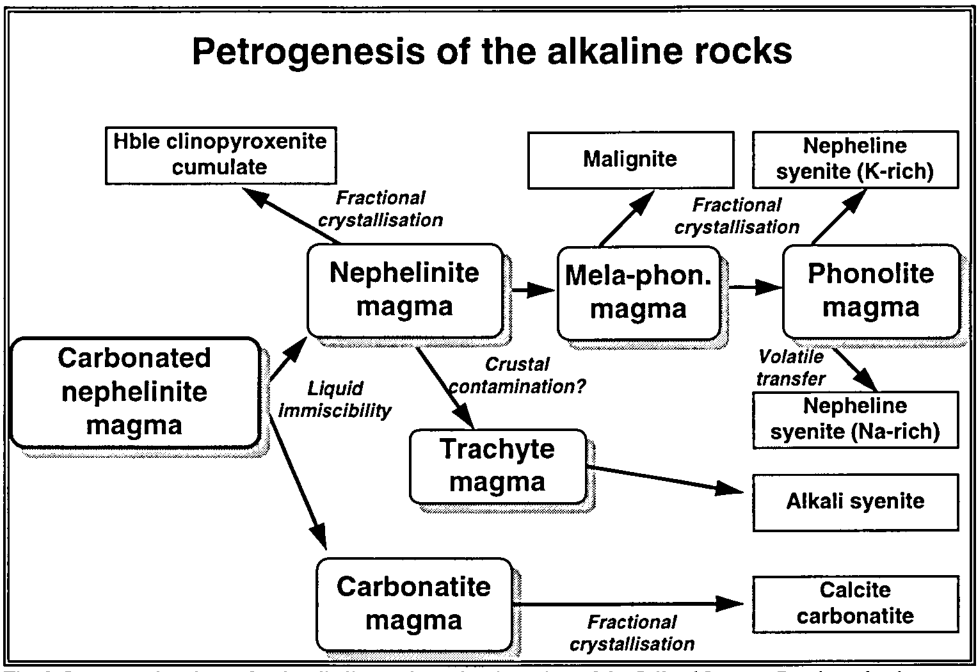

Fig. 2. Petrogenetic scheme for the alkaline rocks and carbonatites of the Seiland Igneous Province that is consistent with the field and geochemical relationships as presently known.

The hornblende clinopyroxenites in the Lillebukt Alkaline Complex contain highly-aluminous Ca- rich pyroxene, indicating that they crystallised from magma with exceptionally low silica activity. They are suggested to have formed by the plating of the walls of fractures through which nephelinite magma saturated in pyroxene, amphibole, apatite and Fe-Ti oxides (but not nepheline) was migrating upwards from depth.

The syenites in the Lillebukt and Breivikbotn alkaline complexes could be postulated as having crystallised from trachytic magmas which were precursors to phonolite. This hypothesis is supported by their emplacement prior to nepheline syenite in the Lillebukt Alkaline Complex. For reasons outlined above, and volumetric relations between syenite and nepheline syenite in the Lillebukt Alkaline Complex, this interpretation is not preferred. Instead, the syenites are regarded as derived from batches of nephelinite or, more probably, phonolite magma which had assimilated significant amounts of quartz-bearing crustal rocks (paragneiss?).

A particularly difficult petrogenetic problem is posed by the regional association of K-rich nepheline syenite with Na-rich nepheline syenite (occurs only as pegmatite dykes). These rocks types have compositions on opposite sides of the thermal minimum in the residua system (SiO_2-$NaAlSi_3O_8$-$KAlSi_3O_8$), and it does not seem possible that they can be related by fractional crystallisation. The preliminary interpretation appeals to the accumulation of volatiles in the upper part of bodies of phonolite magma. The migration of volatiles (chiefly H_2O) resulted in the selective enrichment of Na over K in the volatile-rich pegmatite magma.

9. The tectonic environment of the Seiland magmatic activity

Krill & Zwaan (1987) questioned earlier interpretations of field relationships on which the concept of the Finnmarkian Orogeny was based and suggested that the igneous rocks of the Seiland Province were pre-orogenic, rather than synorogenic. They proposed that the magmatic activity was associated with crustal attenuation and the formation of a rifted margin to the Baltoscandian continent. A similar hypothesis has also been advanced by Andréasson (1987).

Krill & Zwaan (1987) suggested that deformation and metamorphism in the Seiland Province was exclusively Scandian. On the basis of more recent Sm-Nd mineral isochron and U-Pb ages this hypothesis can be rejected. As noted above, the Hasvik Gabbronorite was emplaced at ~700Ma into metasediments that had already experienced 3 phases of deformation. In addition, structural relationships in several areas demonstrate unequivocally that nepheline syenite pegmatite dykes were intruded at 530-520Ma into rocks which had been both deformed and metamorphosed at an earlier stage in the plutonic development of the province. These relationships are conclusive evidence that emplacement of many of the intrusions of the SIP took place after the principal orogenic deformation of the Sørøy Group and much earlier than the Scandian orogenic events.

The high-K, calc-alkaline association of diorite, monzonite, quartz monzonite and monzogranite developed in the Storelv and Husfjord areas of Sørøya (Robins & Gardner 1975) (and possibly in the Øksfjord area), and the field relations demonstrating emplacement of the Storelv Metagabbro between 2 phases of folding of the Sørøy Group, suggest that the earliest igneous activity in the SIP was truly synorogenic. This led Aitcheson (1989) to propose an early «Sørøy Province» and a younger «Stjernøy Province». The emplacement of these earliest intrusions is very poorly constrained, but may have taken place around 800-850Ma.

The later mixed tholeiitic/alkali olivine basalt igneous activity took place during a prolonged period of ~180Ma (from ~700-520Ma). Intrusion took place in this interval at moderate pressures corresponding to mid-crustal level. The metamorphic foliations and high-temperature mineral assemblages that were developed in the country rocks during the igneous activity may be due to some degree to the emplacement and later foundering of the large mafic and ultramafic plutons. It is probable, however, that the magmatism and some of the foliation-producing deformation and metamorphism may have been related to an extensional tectonic regime and crustal thinning.

Interpretation of the Lillebukt Alkaline Complex as a deformed and metamorphosed ring complex (Skogen 1980) suggests that the alkaline suite, in contrast with the older intrusions in the province, was emplaced at a relatively shallow crustal level. Recent work supports this view and leads the authors to the conclusion that the alkaline rocks and carbonatites were intruded after rapid uplift.

Deformation of the alkaline suite and their host rocks during upper greenschist facies metamorphism (Sturt & Ramsay 1965, Ramsay & Sturt 1970) took place after reburial of the SIP, possibly due to nappe emplacement during a subsequent Late Cambrian-Early Ordovician tectonothermal cycle and/or during the Scandian Orogeny, as evidenced by K-Ar and ^{40}Ar-^{39}Ar data, rather than during a continuous "Finnmarkian" (s.l.) strain history as inferred earlier from fold geometry's (Sturt & Ramsay 1965).

The final emplacement history of the Sørøy Nappe is ambiguous. The high-grade metamorphic parageneses in the SIP are clearly allochthonous since cover sequences in the underlying nappes exhibit lower grades of metamorphism. Pre-D2 mylonites along the base of the nappe (Worthing 1971, Akselsen 1980), folding of the nappe boundary on Seiland by folds assumed to be related to D2 structures in the Sørøy sequence and the belief that the nappe boundary is cut by "syn-D2" intrusions (Ramsay *et al.* 1985) suggest an early emplacement. The folding of the nappe boundary is suggested by this author to be related to gravitational tectonics which took place after emplacement of the nappe as a result of a density inversion. The large synforms present on both Seiland and in the Stjernøy-Øksfjord region are cored by thick mafic and ultramafic plutons. These appear to be local expressions of the type of vertical movements which in part led to the preservation of the Seiland Province in a large-scale sag (Fig. 1), as well as the anticlinal tectonic windows exposing the Precambrian Raipas suite and an autochthonous cover sequence on the adjacent mainland (Olesen *et al.* 1990). As far as this author is aware, none of the intrusions belonging to the Seiland Province cut the base of the Sørøy Nappe. The preliminary conclusion is that the nappe was emplaced after c. 523Ma and possibly in connection with the Finnmarkian Orogeny as redefined here (see Table 2). This is in accord with the rather tenuous evidence that Ar-Ar ages of hornblende of c. 490Ma are preserved only in the basal parts of the Sørøy Nappe, possibly due to emplacement of the nappe onto a cooler substrate (Dallmeyer 1988). Final emplacement of the nappe into its present position took place during the Scandian Orogeny.

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GUIDE TO LOCALITIES IN THE HAKKSTABBEN-ALTNESET AREA OF SEILAND.

The traverse from Hakkstabben to Altneset will give an opportunity to examine parts of two of the younger gabbro plutons in the region (the Rognsund Intrusion and the Lille Kufjord Intrusion), basic and ultrabasic dykes, and various types of alkaline rocks and to relate these to the structural, metamorphic, and magmatic evolution of the Seiland Igneous Province as a whole.

The localities described below can be found in numbered order on Maps 1 and 2, taken from Robins (1982) and Robins *et al.* (1991). Grid references refer to Norges geografiske oppmålings M711 series 1:50 000 topographic map of Seiland from 1979, and are given in UTM co-ordinates.

Locality 1. Mantle xenoliths in an ultramafic dyke. Coastal exposure behind the grocery shop at Hakkstabben (1835 I; ED800985).

Dyke of olivine-clinopyroxene hornblendite cutting foliated metagabbro. The dyke contains abundant xenoliths up to 10 cm across of porphyroclastic plagioclase-bearing spinel lherzolite of mantle derivation. In places the dyke matrix consists of hornblende gabbro. This dyke is one of a suite that is widespread on Seiland but which has not been noted elsewhere in the Seiland Province. It can be demonstrated that the xenolithic dykes post-date the youngest olivine gabbro plutons (such as the Rognsund Intrusion, see later in this guide) and predate the emplacement of the alkaline rocks. They appear to represent the youngest phase of the picritic-alkaline olivine basalt magmatism related to the development of the Melkvann Ultramafic Complex which occupies the centre of the eastern half of the island of Seiland. The dykes and their xenoliths have been described in some detail by Robins (1975) and Leaver *et al.* (1989).

Locality 2. Deformed nepheline syenite pegmatite and contact-metamorphic aureole of the Rognsund Intrusion. Shoreline exposures on the N. side of Oldervika (1835 I; ED796986-ED794987).

Deformed nepheline syenite pegmatite which has a length of almost 1.5 km and a width of up to 50 m. It is discordantly emplaced in metasediments and foliated metagabbro, both of which are locally metasomatised, the former into banded fenites containing ægirine augite and alkali feldspar. The dyke at this locality retains a primary lower (western) contact, which is characterised by a marginal facies of syenite pegmatite, while the upper part of the dyke is intensely deformed and consists of protomylonite and mylonite. The latter exhibit a strong sub-horizontal lineation of feldspar and nepheline ribbons. The mylonitic foliation and screens of fenitized gneiss are folded by several generations of tight to isoclinal folds, some of which appear to have nucleated beside porphyroclasts of nepheline. Part of the dyke is occupied by a tectonic breccia consisting of a calcite and biotite-rich matrix containing well-rounded, ellipsoidal pebbles of feldspar, nepheline, protomylonite or mylonite which are coated with a skin of fine-grained biotite. Elongated fragments are statistically aligned within the foliation, and are parallel or at right angles to the lineation in the dyke. The breccia probably was developed from a segregation of carbonatite pegmatite which are present in several nepheline syenite pegmatites (see Locality 6). Note that the deformation is restricted to the dyke and the immediately adjacent country rocks. It was the result of dextral shearing of the dyke between rigid blocks as indicated by the displacement of the contact between gneiss and metagabbro further inland by circa 150 m.

To the east, and more extensively to the west of the deformed pegmatite there are typical shoreline exposures of paragneiss within the contact-metamorphic aureole of the Rognsund Intrusion. The gneiss contains garnet and sillimanite, little biotite and, in places, orthopyroxene, hercynite and cordierite. Mafic dykes which cut second-generation folds in the gneiss are partially to completely transformed into pyroxene granulite. Some dykes are cored by amphibolite and exhibit rinds of granulite along primary and tectonic contacts. Partial melting in the aureole led to the local development of agmatites which consist of a massive granodioritic matrix and fragments of quartzite, calc-silicate and mafic rocks.

The shoreline traverse ends at the contact of the Rognsund Intrusion. Metagabbro just within the contact contains abundant, small, zoned xenoliths which consist of plagioclase, hercynite and accessory corundum as well as larger xenoliths of metasediment that exhibit the same segregations enclosed in a garnet- and biotite-rich matrix. Fine grained, granular gabbros from this locality are believed to be a chilled margin to the Rognsund Intrusion. They have an alkali olivine basalt composition.

Walk from the shore due north to the road, then north-westwards along the road. At Forsbukta, turn to the left and walk south along the shore, passing a small, old quarry to Locality 3.

Locality 3. Hornblende clinopyroxenite dykes, and associated metasomatic rocks. Shoreline on S. side of Forsbukta (1835 I; ED786992).

Here, the Basal Zone of the Rognsund Intrusion contains a large enclosed slab of metasediment and is cut by a dense swarm of mafic and ultramafic dykes (one of which contains xenoliths of lherzolite). These are intruded by narrow, dilational dykes of coarse-grained to pegmatitic, apatite-rich hornblende clinopyroxenite as well as titanaugite syenite and younger hornblende syenite and biotite-magnetite syenite pegmatite. The hornblende clinopyroxenite dykes represent one of the earliest expressions of alkaline magmatism in the Seiland Province. They are associated with wide metasomatic aureoles in which the country rocks are transformed into black, granular, plagioclase-free, hornblende clinopyroxenites containing variable amounts of apatite, due to introduction of Fe^{3+}, Mn, Ca, K and P and removal of Mg and possibly Si (Robins & Tysseland 1979). Despite the intense metasomatism, earlier dykes can still be discerned due to textural variations in the metasomatic rocks. This small area has been described in detail by Robins (1974).

Locality 4. Rognsund Intrusion. Forsbukta (Kræmmervik) to Daudningsberget (1835 I; ED785995-ED779997).

This traverse upwards through the Layered Series of the Rognsund Intrusion, from the poorly exposed Basal Zone in the innermost part of the bay, through the Crescumulate Zone on the north side of the bay to the Cumulate Zone (characterised by the occurrence of cumulus magnetite), illustrates some of the typical magmatic features of the olivine gabbros in the Rognsund Intrusion such as modal and textural layering, minor unconformities and load structures (Robins 1982). The later foliation is normally parallel to the steeply-dipping layer boundaries but in places is axial planar to minor folds of the modal layering. The Basal Zone is cut by hornblende gabbro pegmatites that appear to have been emplaced along a particular horizon in the cumulates. Such pegmatites can form dense swarms in parts of the Seiland Province, particularly within and around the ultramafic complexes. Mafic dykes are extremely common, occur in various orientations and the majority exhibit later foliations. These can be examined in greater detail at Locality 5, reached by walking to the north-west, parallel to the shore, over a low ridge to Grannes.

Locality 5. Dykes emplaced in the Rognsund Intrusion. Grannes (Grandnes) (1835 I; ED774002).

This spectacular, wave-washed locality shows most of the intrusive features of the swarm of mafic dykes which post-dated the Rognsund Intrusion, other olivine gabbro plutons of equivalent age in the region and the ultramafic complexes. The dykes are variable in width and orientation. Many exhibit "horns" where they change direction. It can be demonstrated in these exposures that this is the result of the dilation of adjacent, overlapping fractures. The strips of olivine gabbro, that at an early stage in the dilation connected dyke walls, were bent and fractured before final failure. All the mafic dykes are cut by variably-sheared syenite pegmatites. Elsewhere in the area, such pegmatites predated the emplacement of nepheline syenite pegmatites.

The mafic dykes vary from blastoporphyritic amphibolite with relic phenocrysts of olivine and calcium-rich pyroxene to foliated amphibolites devoid of primary minerals. They vary compositionally from picrites and ankaramites to alkali olivine basalts, all exhibiting trace-element signatures corresponding to within-plate basalts (Robins & Takla 1979).

Return to the road at Skarvevatnet, walk towards Altneset and turn left along the side road to Skarveberg. Locality 6 is about 150 m. to the south of the road, at the edge of the birch forest.

Locality 6. Zoned nepheline syenite-carbonatite pegmatite. Old mica mine, Skarvbukt (1835 I; ED777014).

Pegmatite emplaced into the Rognsund intrusion with a nepheline syenite marginal zone, an intermediate zone of apatite-rich syenite and a core of carbonatite (Robins 1972). The outer margin of the core is defined by large euhedral crystals of sodium-rich alkali feldspar (in places intergrown with euhedral apatite) and giant kinked books of biotite. Pegmatites such as this demonstrate a genetic connection between the nepheline syenite and carbonatite intrusions present in the province.

Locality 7. Crescumulates and hornblende gabbro pegmatites Skarveberg (1835 I; 772018).

These exposures of the uppermost part of the Crescumulate Zone of the Rognsund Intrusion show the characteristic skeletal olivines and elongated Ca-rich pyroxenes, both elongated at a high angle to the modal and textural layering. Slender, branching and skeletal olivines are up to 1m long, suggesting rapid upward growth from the magma chamber floor into stagnant, undercooled magma. Individual plates of olivine are generally enclosed in plagioclase, but plagioclase and olivines are separated by 2 pyroxene-spinel symplectites. The later hornblende gabbro pegmatite dykes are emplaced along the modal layering of the olivine gabbros and exhibit comb textures, the skeletal amphiboles having grown inwards from the dyke margins.

Locality 8. Metasediments of the Eidvågeid Sequence. Roadcuts at Hestneset (1835 I; ED773029).

The paragneiss which has been referred to as "garnet gneiss" (Hooper 1971) and more recently as the Eidvågeid Supracrustal Sequence (Akselsen 1982, Rice 1990) is well exposed in roadside exposures, sufficiently distant from the Rognsund and Lille Kufjord intrusions that contact-metamorphism is minor. The paragneiss is strongly foliated and contains, in addition to muscovite-free quartzofeldspathic layers with ubiquitous pink garnet, biotite and sillimanite (derived from pelite and semipelite?), bands of quartzite and calc-silicate. The highly-modified lithological layering is deformed by tight to isoclinal, similar-type folds of at least two generations which result in complex interference patterns.

Locality 9. Margin of the Lille Kufjord Intrusion. Road cut south of Altneset and shore exposures on Altneset (1835 I; ED769035-ED766039).

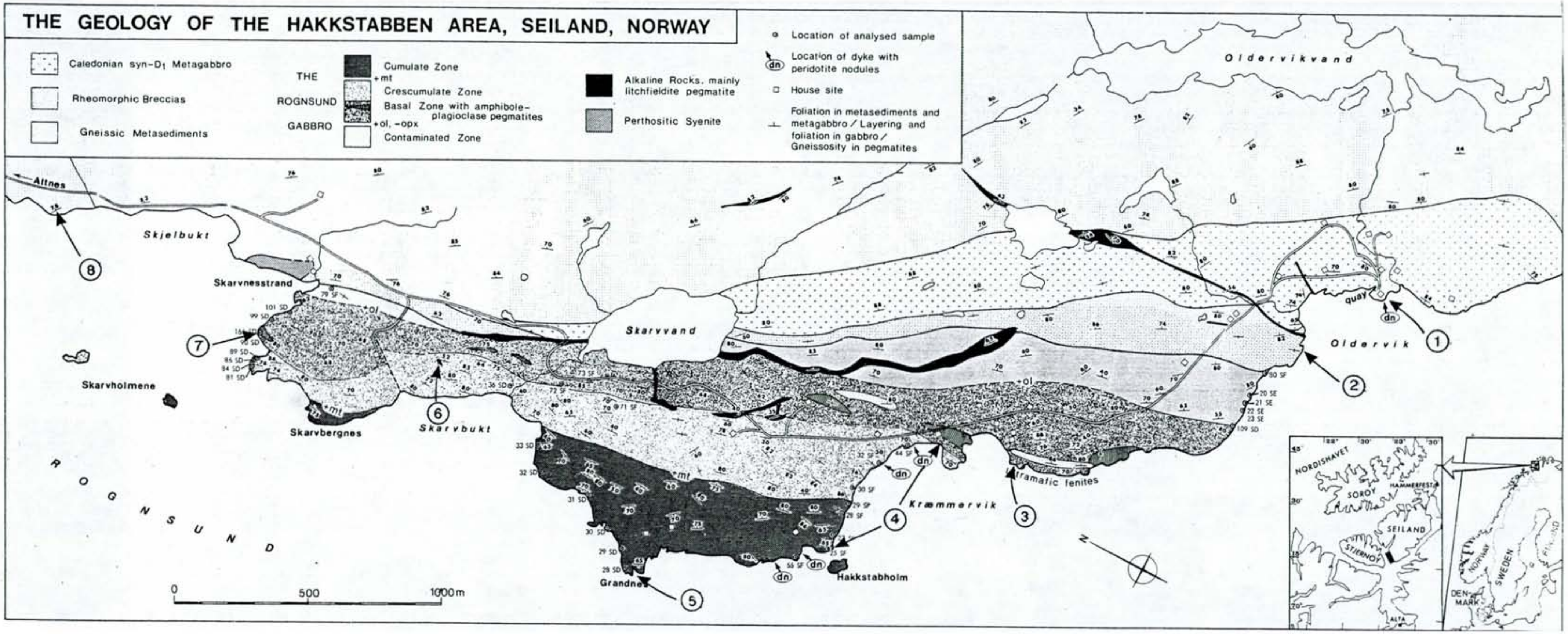
Near-vertical contact between paragneiss and the tholeiitic Lille Kufjord Intrusion (dated by a Sm-Nd internal isochron to 488±57 Ma). Near the contact the paragneiss contains less biotite than elsewhere and the mica appears to have grown at the expense of a contact-metamorphic assemblage including garnet, sillimanite, cordierite, hercynite and rutile in aluminous lithologies and hypersthene in less aluminous rocks. Hercynite is generally enclosed in sillimanite and garnet, suggesting that hercynite and quartz coexisted at the highest temperatures attained during contact metamorphism. The compositions of coexisting garnet and cordierite suggest equilibration during cooling of the aureole rocks (to temperatures of 650-700^{o}C) at a pressure in the lower part of the range of 5.4 - 8.2 kb (Robins *et al.* 1991).

Medium to pegmatitic, massive quartz gabbronorite, containing fist-size crystals of garnet, immediately within the vertical contact of the Lille Kufjord Intrusion forms the outer few meters of the up to 100m-thick Marginal Series. These rocks pass inwards into heterogeneous olivine gabbronorite and gabbronorite characterised by a more or less pronounced, steeply-dipping layering defined by variations in grain size and, to a lesser extent, modal composition. The Marginal Series has a sharp, discordant contact (not exposed on Altneset) with olivine gabbro, which constitutes Lower Zone b of the Layered Series. The magmatic fabric in these LZb rocks dips at a primary, shallow angle towards the interior of the intrusion.

Locality 10. Layered Series (LZb) of the Lille Kufjord Intrusion. Shoreline from Altneset to the ferry quay (1835 I; ED766039-ED773044).

In this traverse the modal layering in the Lille Kufjord Layered Series is disposed in an open syncline. This structure, which may also be visible in the cliff section on the opposite side of Store Kufjorden, must be a primary feature of the intrusion. This is in contrast with the steeply dipping modal layering of the adjacent, and older, Rognsund Intrusion. The LZb olivine gabbro contains abundant, aligned aluminous xenoliths, similar to those near the margin of the Rognsund Intrusion, as well as less frequent, but much larger xenoliths of pegmatitic gabbronorite which apparently were derived from collapse of parts of the Marginal Series from the walls of the magma chamber. The Lille Kufjord Intrusion is cut by mafic dykes compositionally similar to those in the Rognsund Intrusion, and in addition, syenite and nepheline syenite pegmatites (although no pegmatites are present along this traverse).

Map 1. The geology of the Hakkstabben area, Seiland, Norway.



Map 2. Geological map of the Lille Kufjord Intrusion