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Geochemistry of platinum metals in rocks and ores in Norway: Pilot project.

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The results of analysis. For platinum elements and gold are presented c. 385 samples (from existing collections) from a range of geological environments. Just under half of the analytical work (c. 185 samples analysed by AAS and INA) was financed by the pilot project. C. 140 of these samples are from Ni-Cu deposits, chromite deposits in ophiolitic rocks or chromite-bearing rocks in ophiolites. The remainder are from weakly mineralized parts of layered ultramafic - mafic intrusions, komatiites, Alaskan-type ultramafic intrusions and eclogites.

Two small Ni-Cu deposits, both in oceanic crustal rocks, contain > 5 ppm PGE + Au. Several Ni-Cu deposits of small to intermediate tonnage contain > 1 ppm PGE + Au. The most interesting result economically are 3.6 ppm (Os + Ir + Ru) from a chromite-bearing dunitic cumulate in the Leka ophiolite and values > 0.5 ppm PGE from chromitites in three isolated ultramafic bodies. Values found in other environments were low.

Recommendations are given for further work in the ophiolitic environment and elsewhere.

Emneord		
	Kobber	
Edelmetall	Krom	
Nikkel		

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SUMMARY

Objective of the research

This project consisted of a pilot study on platinum group elements (PGE) in Ni-Cu sulphide and Cr mineralizations in Norway.

The world's most important PGE deposits (Merensky, Johns-Manville) (minor Ni-Cu) are often associated with chromite enrichment in layered intrusions, and chromite concentrations in other geological environments are also known to have anomalously high concentrations of PGE. Much of the world's PGE production (eg. from Norilsk and Sudbury) comes, however, as a by-product from mining of Ni-Cu deposits. Many less important Ni-Cu mines have a significant and, in some cases, economically vital income from by-product PGE. It is thus appropriate to make an inventory of those mineralizations in Norway which are of a type for which the PGE are known to have geochemical affinity: two Ni-Cu deposits, one of them exceedingly small, were already known to have high PGM contents - possibly averaging 5 ppm or more.

The pilot project involved analysis of representative suites of samples from a number of Norwegian Ni-Cu deposits from different geotectonic environments and from podiform chromite deposits.

Data on PGE in other environments have also been included in the draft final report in order to give as complete an overview of PGE in rocks and ores in Norway as possible. The report thus includes data from the following environments:

- Ni-Cu sulphide deposits (potential for biproduct Pt-Pd),
- large layered intrusions (potential for sulphide-related Merensky-type Pt-Pd ore and chromite-related UG-2 type Pt-Pd ore)
- komatiites (general potential for Ni-Cu-PGE),
- ophiolites and related rocks (potential for chromite-related Os-Ir-Ru, possibly also Pt-Pd),
- Alaska-type ultramafic instrusions (potential for chromite-related Pt).

Materials and methods

The pilot project had a total marginal cost budget of NOK 85,000 and an initial duration of nine months. These constraints dictated that maximum information could be gained by analysis of representative suites of samples from existing collections, without additional field work. Analysis of c. 185 samples was financed by the pilot project: the report includes results from an additional c. 200 samples the analysis of which has been financed from other sources.

The analytical aim in this project has been to determine as may of the PGE as possible, at levels as close as possible to their anticipated background concentrations in the rocks concerned, i.e. to a level of c. 0.1 ppb for Ir and 1 ppb for the other PGE (Crocket 1981). Commercial laboratories do not currently offer analysis at the levels desirable for all the PGE in all the types of sample involved, but time constraints precluded the option of using a range of research methods.

The compromise solution has involved the use of the best commercially available methods known to us and the acceptance of the limitations this imposed on the number of samples which could be analyzed. Two methods were used:

- atomic absorption spectrometry (AAS) using electrothermal atomization after preconcentration in silver-lead beads. This method was used for samples containing > 10% chromite as these cannot be analyzed adequately by the other method considered, instrumental neutron activation analysis (INAA) using a nickel-sulphide bead because the chromite hampers formation of the bead and because of interference problems. This method is however only suitable for Pt, Pd and Au.

- all other samples were analyzed by INAA after preconcentration in a nickel-sulphide bead. Given the low concentrations in most of the samples the results must be considered good. Interference effects inherent in the method give unreliable results for Pd and Rh in samples with >5% Cu and unreliable Pt results in samples with high Au contents: these effects are generally coincident.

Analysis of results

Data from nine Ni-Cu deposits are presented. The results from four of these are from published sources while the data from the remaining five (53 analyses) are new. The two largest deposits, Bruvann (Råna) and Flåt contain unusually low concentrations of PGE. Two deposits of small to intermediate size, Vakkerlien and Espedalen, contain > 1 ppm (PGE + Au) in 100 % sulphide: a third, Skjækerdalen does also, but this is due to one unusually high Pd value. Two of the smaller deposits, Fæøy and Lillefjellklumpen, both from ophiolites ('sensu lato') have higher PGE contents, > 5 ppm. Au-rich Cu>>Ni mineralizations at Hosanger, Flåt and Ertelien are probably of very limited extent.

Data are presented from two intrusions, Tverrfjell (Råna) and Lille Kufjord, of which parts have been assessed for Merensky-type Pt-Pd mineralization. Neither area has yielded values indicating the presence of such a mineralization.

Twenty-nine samples of komatiite from two areas in N. Norway, Karasjok and Skjomen, were analyzed: The average concentrations resemble those from komatiites elsewhere in the world and, apart from one sample with 82 ppb Au, no anomalous values were found.

Sixteen samples of chromite-bearing dunitic cumulate from the Leka ophiolite included one with highly anomalous contents of Os-Ir-Ru (1070, 1760, 770 ppb respectively). In that this sample appears to represent part of a tabular layer, the potential may exist for an extensive mineralization. Four of the remaining samples were weakly anomalous (50 - 200 ppb Os+Ir+Ru).

Sixty-nine samples of chromitite from isolated ultramafic bodies were analyzed. Because of the analytical method which had to be used only Pt, Pd and Au were determined. Samples from three deposits, Osthammaren, Aurtand and Ørnstølen, gave values of (Pt+Pd+Au) > 500 ppb while samples from Skamsdalen gave 286 ppb (Pt+Pd+Au).

Twenty-one samples from two Alaskan-type ultramafic intrusions in N. Norway, Melkvann and Reinfjord, were analyzed. None of the samples was chromite-bearing and in none of them did the content of any of the PGE or Au exceed 10 ppb.

Seventeen samples of eclogite only gave values consistently over detection level for Au (ave. 2.7 ppb).

Conclusions

A considerable amount of data has been accumulated in the course of the pilot project, much of it of scientific interest. Results from only one of the geotopes sampled, ophiolites and related rocks, give an indication of possible economic interest. The specific targets located so far which are considered to merit further study are:

- chromite-olivine cumulates in the Leka ophiolite

- chromite-bearing harzburgites forming isolated ultramafic bodies ie. Osthammaren, Skamsdalen, Aurtand and Ørnstolen.

Critical topics to be examined in the Leka ophiolite will be the lateral and vertical extent of Os-Ir-Ru enrichment, geochemical variation within the enriched zone, the mineralogical residence of the PGE and the processes leading to their concentration.

In the isolated harzburgitic bodies the critical question in an economic evaluation will be whether the PGE are exclusively linked to chromite. All the chromite mineralizations found to date are very small. Similar problems to those indicated above will have to be studied should it prove that some of the PGE have a broader occurrence. These problems have otherwise a considerable scientific interest.

The pilot project permitted analysis of samples from only a few of the potential targets of this type. Others would certainly also have revealed anomalous values and a more thorough inventory should be considered.

In the other geotopes examined, further PGE studies with an economic goal should be conditional on the identification of more 'prospective' targets, eg. sulphide-bearing komatiites, intrusives of komatiitic parentage, chromite-bearing dunites in the Seiland Province.

Two possible geotopes remain to be sampled. These are the cover sequences overlying ophiolites, where there is a potential for fossil placers, and black shales. At least in the first case it should be possible to use Cr as an indicator for PGE.

2. INTRODUCTION

This report presents the results of a pilot study of platinum group elements (PGE) in rocks and ores in Norway: The study has been financed by the Royal Norwegian Council for Scientific and Industrial Research (NTNF) and by the Geological Survey of Norway (NGU), in connection with Norway's associate membership in the European Economic Community (EEC) Raw Materials Programme. The pilot study is intended as a forerunner for a more thorough evaluation of one or more of the environments regarded as having a potential for PGE mineralization.

The world's most important PGE deposits (Merensky, Johns-Manville) (minor Ni-Cu) are often associated with chromite enrichment in layered intrusions, and chromite concentrations in other geological environments are also known to have anomalously high concentrations of PGE. Much of the world's PGE production (eg. from Norilsk and Sudbury) comes, however, as a by-product from mining of Ni-Cu deposits. Many less important Ni-Cu mines have a significant and, in some cases, economically vital income from by-product PGE. It is thus appropriate to make an inventory of those mineralizations in Norway which are of a type for which the PGE are known to have geochemical affinity: Two Ni-Cu deposits, one of them exceedingly small, are known to have high PGM contents - possibly averaging 5 ppm or more.

The pilot project involved analyses of representative suites of samples from a number of Norwegian Ni-Cu deposits from different geotectonic environments and from podiform chromite deposits.

The platinum metals are: ruthenium, rhodium, palladium, osmium, iridium and platinum (Table 1). For petrological purposes they are normally ranked in order of descending melting point, from osmium to palladium. Gold, though not a PGE, has an occurrence and behaviour in mafic and ultramafic rocks which has much in common with the low-melting-point PGE and as the commonly used analytical methods also give values for gold, it will also be considered in this report.

	Ru	Rh	Pd	Os	Ir	Pt	Au
Z	44	45	46	76	77	78	79
m.p. C	2310	1966	1552	3045	2410	1722	1063

Table 1: Atomic numbers and melting points for the PGE and gold. Melting points are taken from Weast (1975).

All of the PGE have uses as catalysts or in alloys, as well as in other specialized applications. Their prices range from $124/ troy oz. for Pd to $1200/troy oz. for Rh (Mining Journal, 6.2.87).

The word 'geotope', borrowed and modified from the world of biology by the Norwegian geologist Tore Vraalstad, can be used to indicate an environment favourable for the concentration of specific elements. Potential geotopes for PGE in Norway are:

- Ni-Cu sulphide deposits (potential for biproduct Pt-Pd),
- large layered intrusions (potential for sulphide-related Merensky-type Pt-Pd ore and chromite-related UG-2 type Pt-Pd ore)
- komatiites (general potential for Ni-Cu-PGE),
- ophiolites and related rocks (potential for chromite-related Os-Ir-Ru, possibly also Pt-Pd),
- Alaska-type ultramafic intrusions (potential for chromite-related Pt),
- palaeoplacers derived from ophiolites (extensive cover sequences in part derived from underlying ophiolites and locally palaeoweathering profiles are known) and
- black shales. Certain levels in the Cambrian Alum Shales in the Oslo area are known to be enriched in Cr and Ni (Bjørlykke, 1974) and it is conceivable that PGE are also enriched in this environment.

3. ANALYTICAL METHODS

The analytical aim in this project has been to determine as many of the PGE as possible , at levels as close as possible to their anticipated background concentrations in the rocks concerned, i.e. to a level of c. 0.1 ppb for Ir and 1 ppb for the other PGE (Crocket 1981). The case for this aim is that the less expensive analytical methods involving determination of Pt and Pd only, at detection levels of 20-50 ppb, gives little opportunity to gain information on the general distribution of Pt and Pd in non- or weakly anomalous samples and are not useful in environ-ments where the potential is for Os and Ir, rather than Pt and Pd. Commercial laboratories do not currently offer analysis at the levels desirable for all the PGE in all the types of sample involved but time constraints precluded the option of using a range of research methods.

The compromise solution has involved the use of the best commercially available methods known to us and the acceptance of the limitations this imposed on the number of samples which could be analyzed. Two methods were used:

- atomic absorption spectrometry (AAS) using electrothermal atomization after preconcentration in silver-lead beads. This method was used for samples containing > 10% chromite by Caleb Brett Laboratories of Manchester. Such samples cannot be analyzed adequately by the other method considered, instrumental neutron activation analysis (INAA) using a nickel-sulphide bead because the chromite hampers formation of the bead and because of interference problems related to Cr. This method is however only suitable for Pt, Pd and Au. Blind standards indicated that the results obtained for Rh were unsatisfactory (an order of magnitude too low) and that the Au values were probably too high, possibly by a factor of 2 (Table 2).

- all other samples were analyzed by Becquerel Labs. of Toronto using INAA after preconcentration in a nickel-sulphide bead. Given the low concentrations in most of the samples the results must be considered good. For high levels, for which SARM-7 was used as a standard (Table 2), levels were within 10% of accepted values for Ru, Pt and Pd and within 20% for Ir, Rh and Au. At intermediate levels (Ax 26) discrepancies are < 30%. A standard with low concentrations of PGE(Tv84) showed significant discrep - ancies for Ir (x 2.7) and Au (x 0.27). Interference effects inherent in the method give unreliable results for Pd and Rh in samples with >5% Cu and unreliable Pt results in samples with high Au contents: these effects are generally coincident.

	Tv 84			Ax 26			SARM - 7	
	Accepted value (Barnes 1986)	AAS (Caleb Brett)	INAA (Becquerel)	Accepted value (Barnes 1983)	AAS (Caleb Brett)	INAA (Becquerel)	Accepted value (Steele 1979)	INAA (Becquerel)
Os	< 2	n.d.	< 2	< 5	n.d.	< 2	83	62
Ir	0.1	n.d.	0.27	2	n.d.	2.7	74	88
Ru	< 10	n.d.	< 10	< 18	n.d.	< 10	430	470
Rh	0.6	n.d.	< 1	8.5	n.d.	9	240	204
Pt	2	< 3	< 10	51	43	35	3740	3475
Pd	< 20	< 2	< 10	73	110	87	1530	1585
Au	4.2	10	1.2	12	28	8.8	310	275

Table 2: Comparison of PGE analyses of three standards analyzed at the laboratories used in this project. n.d. = not determined.

	Os	Ir	Ru	Rh	Pt	Pd	Au
AAS	n.a.	n.a.	n.a.	2	3	2	1
INAA	2	0.2	10	1	5	3	0.5

Table 3: Detection levels in ppb for the analytical methods used. For samples with high Au contents analyzed by INAA the detection levels were 10 ppb for Pt and Pd and 20 ppb for Rh and Ru.

4. GEOLOGICAL ENVIRONMENTS SAMPLED AND RESULTS

4.1 Ni-Cu deposits in mafic intrusives.

Norway has a long tradition in mining and prospecting for Ni-Cu ores, aspects of which are reviewed in a recent paper (Boyd & Nixon, 1985). Pt and Pd analyses with detection levels of the order of 20 - 100 ppb were published for six Norwegian Ni-Cu deposits as long ago as 1932 (Foslie & Johnson Høst 1932). Knowledge of the PGE content of Norwegian orebodies did not advance, however, until 1979 when the first modern PGE analyses, with detection levels of the order of 0.1-5 ppb were published for the Espedalen deposit, Fig. 1, by Naldrett et al. (1979). Data have subsequently been reported for the Vakkerlien deposit (Thompson et al. 1980), for the Lillefjellklumpen deposit (Grønlie 1984, 1976, in press), for the Bruvann deposit (Boyd et al. 1986, in press) and for weakly-mineralized layered rocks from Tverrfjell, Råna (S.-J. Barnes 1986a,1986b,in press). This report will, for the sake of completeness, include the results already published. The latitude and longitude of the deposits, enabling location on Plate 1 are given in the Appendix, Table 1.

The deposits for which data are presented in this report are:

BRUVANN: This is Norway's largest Ni-Cu deposit and one of the largest Ni-Cu sulphide deposits in Europe, the Soviet Union excluded. It is a predominantlty low-grade, disseminated mineralization (Appendix 1, Table 1) (Boyd & Mathiesen 1979) in ultramafic cumulates in the northwestern part of the Råna intrusion (Fig. 2). The host intrusion was probably emplaced into its now allochthonous country-rock gneisses during a tensional episode within the Caledonian orogeny.

SKJÆKERDALEN: This deposit is associated with metagabbroic and ultramafic fragments in magmatic breccias in a small but complex, polymagmatic intrusive in the Gula Group within the Caledonian Trondheim Nappe (Fig. 1, Plate 1). PGE data are reported for this deposit for the first time.

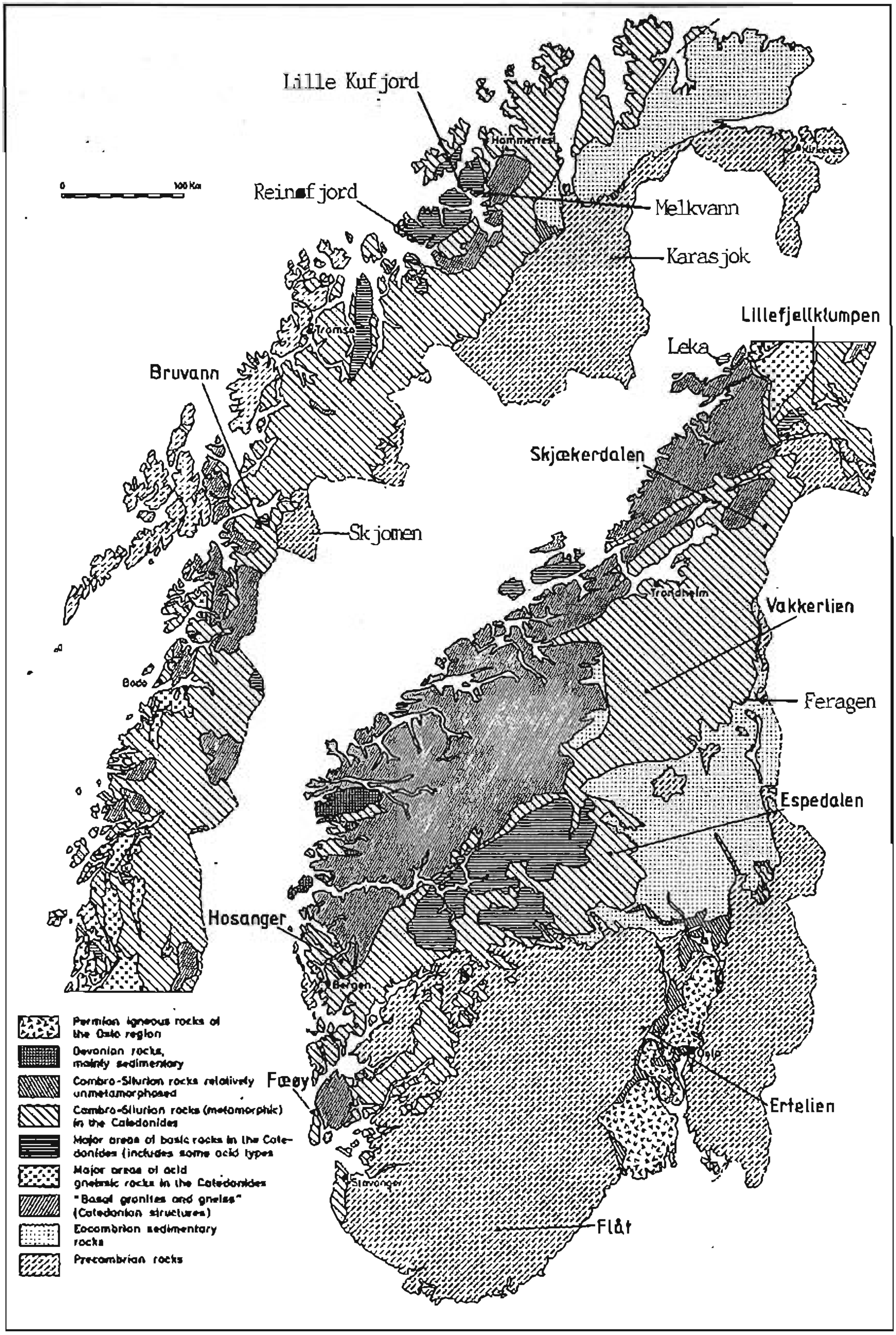

Fig. 1. Location of Ni-Cu deposits and other localities mentioned in the text.

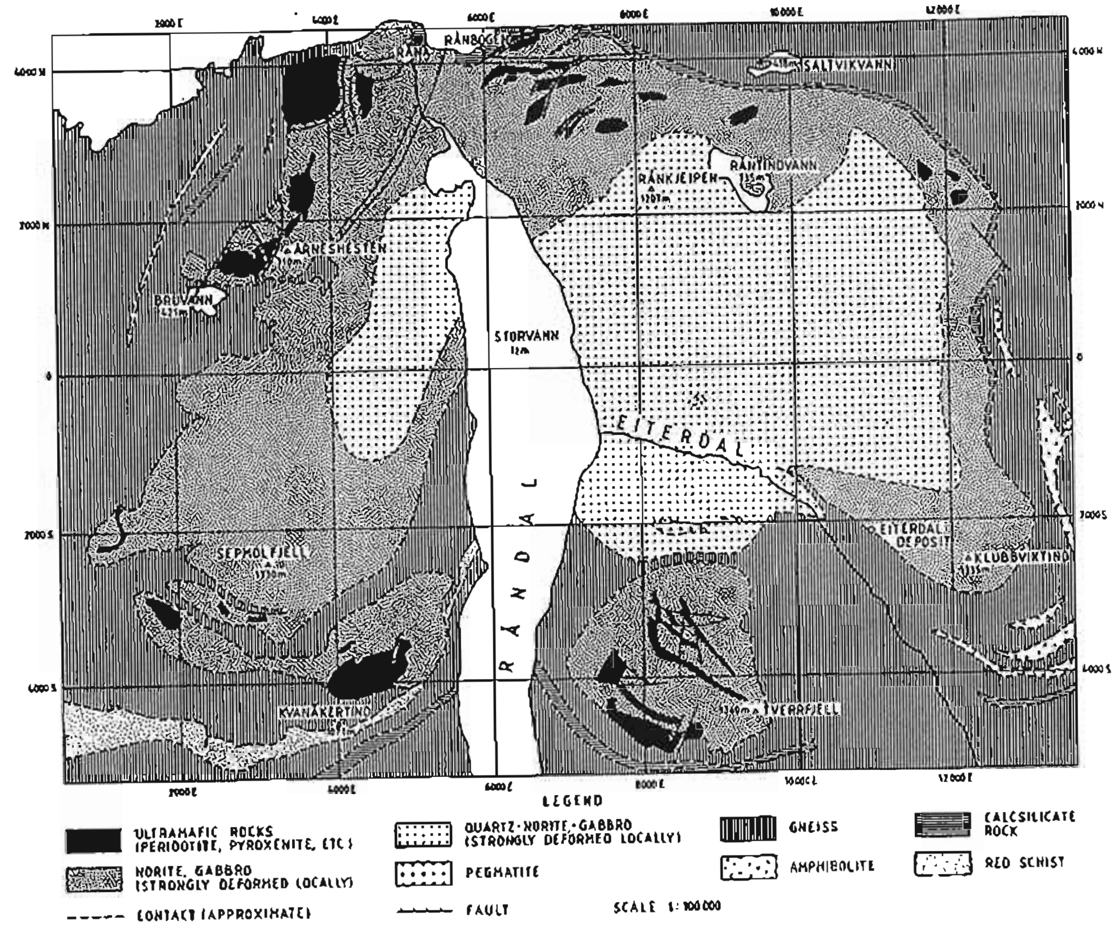

Fig. 2. Geological map of the Råna intrusion (from Boyd & Mathiesen 1979).

VAKKERLIEN: The Vakkerlien intrusion and its associated Ni-Cu mineralization have been described by Thompson et al. (1980) who also presented PGE data. The mineralization includes vein-, stringer- and disseminated types, all dominated by pyrrhotite, pentlandite and chalcopyrite, but with pyrite in most samples. The mineralization occurs in the core of an ultramafic-mafic sill in the Gula Group within the Caledonian Trondheim Nappe (Fig. 1, Plate 1). It has been deformed and metamorphosed under amphibolite facies conditions.

HOSANGER: This deposit is located within a noritic sill in the Anorthosite Complex of the Bergen Arc System, possibly an outlier of the Jotun Nappe (Kvale 1960). It is Proterozoic in age and experienced granulite facies metamorphism at 1064+24 Ma (Sturt et al. 1975). The mineralization includes disseminated to matrix sulphide near the base of the intrusion and veins of both Ni- and Cu-rich sulphide (Bjørlykke 1949). The deposit was mined intermittently from 1883 to 1945. Modern PGE data are presented here for the first time.

ESPEDALEN: The Espedalen deposit is located in an ultramafic-mafic intrusion, one of the second of three suites of mafic intrusives, in an outlier of the Jotun Nappe (Heim 1981), and is therefor also of Proterozoic age. It includes disseminated and breccia mineralization. PGE data were published by Naldrett et al. (1979).

ERTELIEN: This deposit is associated with a small noritic plug (600 m x 450 m), the emplacement of which predated the Sveconorwegian orogeny. Mineralization includes massive, breccia and disseminated types near the margin of the plug.

FLÅT: This deposit occurs within the Evje-Iveland amphibolite complex, probably similar in age to Ertelien. It includes disseminated and massive mineralization. It is Norway's second largest deposit and was mined until 1944.

LILLEFJELLKLUMPEN: This small mineralization (< 100 t Ni metal) forms a massive sulphide lens lying concordantly between primitive MORB-type metabasalt and metagabbro in the allochthonous Gjersvik island arc complex in the Caledonides (Grønlie 1984, 1986, in press). PGE data come from Grønlie (in press) though it has long been known that the body is rich in PGE (Foslie & Johnson Høst 1932).

FÆØY: This mineralization is also from an oceanic environment in that it forms a massive mineralization within the dyke complex in the Karmøy ophiolite. The data presented here are new though also this body was known to have high PGE levels (Foslie & Johnson Høst 1932; Boyd & Nixon 1985).

Form of data presentation

It is a well-established convention that PGE data for Ni-Cu sulphide deposits are presented recalculated to 100% sulphide and then, in diagrammatic form, normalized to concentrations in chondrites (Naldrett et al. 1979; Naldrett 1981). The case for recalculation to 100% sulphides is based on the assumptions that the PGE are collected by sulphide droplets where these are present in quantity and that major disturbance of the concentrations by later alteration has not taken place, and on the advantage in comparing data from different deposits given by the removal of effects caused by variable content of gangue in the samples analyzed. The two assumptions do not hold for sulphide-poor rocks. The use of chondrites as a standard rather than the mantle (which would be logical as the rocks are mantle-derived) is probably due to the availability, in the late 1970s, of reliable data on the content of all the PGE in chondrites(McBryde 1972; Crocket 1974), while such data were not available for mantle rocks, in which concentrations of the PGE and Ni are roughly 0.01 x chondrite values, though for Cu the factor is 0.175). The choice of values to represent the mantle is still fraught with difficulties and reliable data are not available for all the PGE. Normalization to mantle values does, however, have the advantage of facilitating the incorporation of any of the base metals into the diagram while retaining a relatively smooth pattern, also for Cu. The alternative forms of presentation are discussed by Barnes et al. (in press).

The data from Norwegian Ni-Cu deposits are presented in Appendix 1, Table 1. The data for Ni-Cu deposits are presented diagramatically according to the convention established by Naldrett et al. (1979) while data from other environments are presented diagramatically normalized to mantle values as compiled by Barnes et al. (in press).

Results

The deposits have been divided into three groups based on their PGE content in 100% sulphides.

Group 1, Bruvann, Hosanger and Flåt, three of the four largest deposits in the country, have concentrations of PGE an order of magnitude below chondrite for all PGE except Pd, which is just over 0.1 x chondrite (Fig. 3a). Concentrations of Pt and Pd are similar for all three and the concentrations of all PGE are similar for Hosanger and Flåt, while Bruvann has much lower concentrations (< c. 0.01 chondrite) of Os, Ir, Ru and Rh. Few Ni-Cu deposits are recorded in the literature as having comparably low values of Pt and Pd: The two known to the authors are Pipe

(Naldrett et al. 1979) and Montcalm (Naldrett & Duke 1980). The Pd/Ir ratios, indicative of the degree of fractionation of the PGE, are low for all three deposits. Hosanger and Flåt have, in general, patterns similar to those of typical komatiites (Naldrett 1981), though the concentrations are an order of magnitude lower. Some consideration has been given to the problem of explaining the low PGE grades seemingly at variance with evidence of relatively primitive magmas from other indicators, as is the case for Bruvann (Boyd et al. in press) and for mineralizations in the Råna Intrusion in general (Barnes, in press). No conclusion has been reached as to whether the parental magmas were derived from an already depleted mantle or whether PGE were removed in the crust but below presently accessible levels: The weight of evidence, particularly REE data (Barnes 1986), supports the second alternative (see 3.2).

The position of Au for Flåt and Hosanger refers to Au-poor Ni-Cu ore (Au is concentrated in Cu>>Ni mineralization in these deposits), while at Bruvann high Au values occur locally in disseminated Ni-Cu mineralization and no Cu-rich paragenesis is known to exist (after a total of 28,500 m of drilling and several thousand assays). The data for Cu-Au-rich parageneses are considered separately below.

Group 2 (Fig. 3b), Skjækerdalen, Vakkerlien, Espedalen and Ertelien, contain Pt and Pd at higher levels than Group 1, but < chondrite, except for Pd at Skjækerdalen. The ave. Pd content at Skjækerdalen is, however, perhaps artificial, as one of the seven samples was unusually rich (4.7 ppm). Rh values from Espedalen and Vakkerlien are also markedly higher than those found in Group 1 deposits. For Espedalen, Ertelien and Skjækerdalen the contents of Os, Ir and Ru are similar to, or less than those found in Group 1, with all deposits for which data was obtained showing flat patterns for these elements. Though the Pd/Ir ratios of Group 1 and Group 2 deposits overlap, they are generally higher in Group 2, especially for Ertelien, the Pd/Ir ratio of which is compatible with equilibration with a magma of composition between continental tholeiite and MORB.

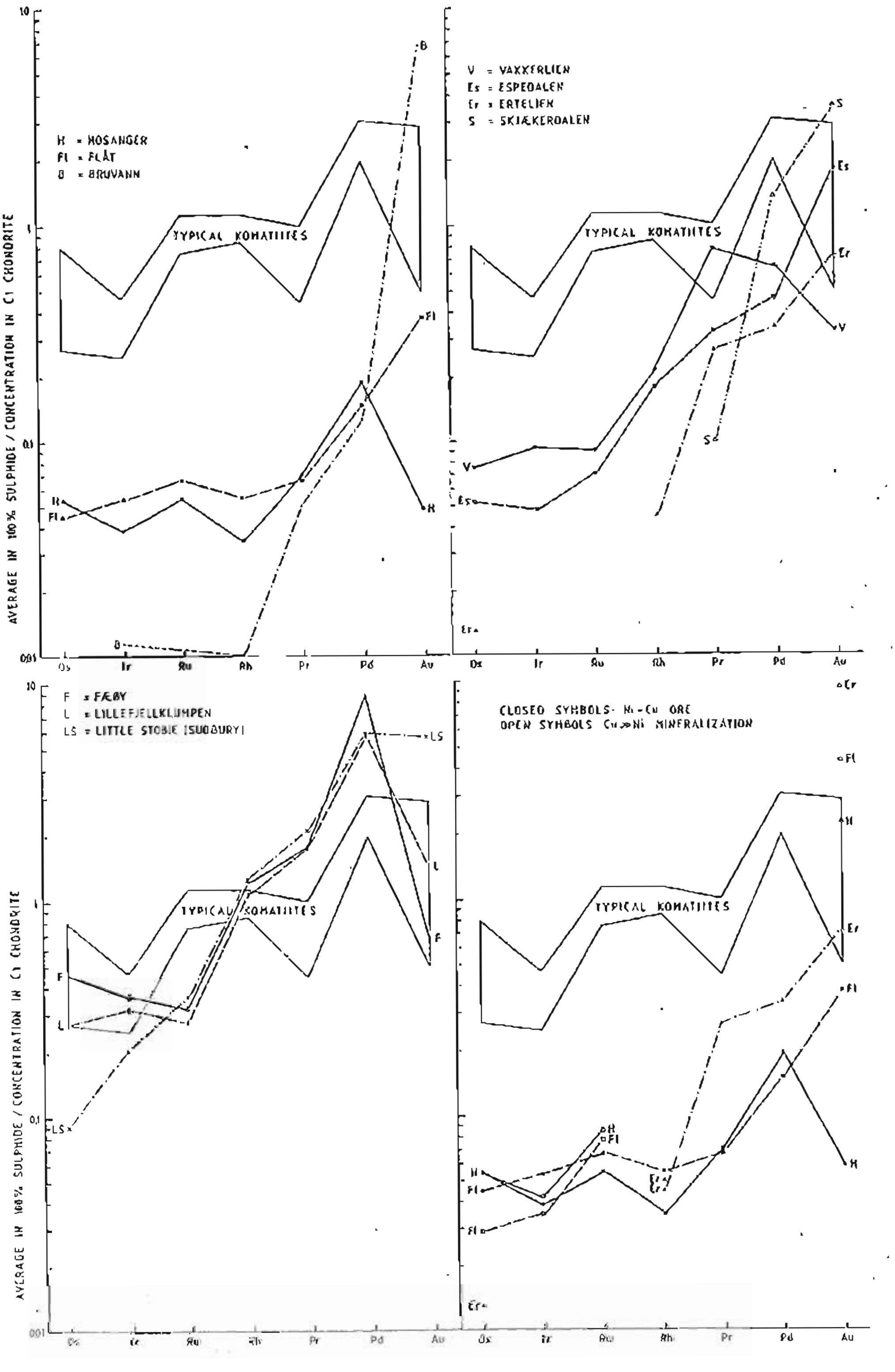

Fig. 3: Average chondrite - normalized PGE and Au contents in 100 % sulphide in Norwegian Ni-Cu deposits. Published data are included from Naldrett et al. (1979) (Espedalen), Thompson et al. (1980) (Vakkerlien), Grønlie (1984) (Lillefjellklumpen), Boyd et al. (1986) (Bruvann).

Group 3, Lillefjellklumpen and Fæøy (Fig. 3c) have Pt and Pd contents exceeding those of typical komatiites, while having concentrations similar to komatiites for Os, Ir, Rh and Au, and relatively low levels for Ru. The patterns for the two deposits are very similar. The concentrations of Pt and Pd are about half of those found in the ophiolite-hosted Illinois River massive sulphide deposit in Oregon (Foose 1986) and the levels for all PGE are about an order of magnitude lower than those found in the chromitite-associated Cliff mineralization in the Unst ophiolite, Shetland (Prichard et al. 1986), though the proportions are similar for Ir, Pt and Pd. Chromitite-associated sulphide mineralization in the Eretria area of the Othris ophiolite has, however much lower Pt and Pd levels (Economou & Naldrett 1984) than those found at Lillefjellklumpen and Fæøy.

Three of the deposits examined, Hosanger, Flåt and Ertelien, contain parageneses dominated by Cu (with Cu/(Cu+Ni) > 0.9) (Fig. 3d). For reasons already discussed, no data are available for Pt and Pd, and in two cases for Rh, in the Cu-rich parageneses. The Ertelien Ni-Cu mineralization has exceedingly low contents of Os, Ir and Ru, with even lower contents of Os and Ir, and probably also of Ru, in the Cu>>Ni mineralization. At somewhat higher levels the same is true for Os and Ir at Flåt, while the Cu-Ni paragenesis at Hosanger has higher levels of Ir and Ru, and the same Os content as the Ni-Cu ore.

Cu-rich veins and/or ore bodies are known from many Ni-Cu deposits, including several at Sudbury as well as Katiniq, Alexo and Insizwa. Alternative explanations for this enrichment have been:

- Hydrothermal mobilization of Cu, Pt, Pd and Au (McCallum et al. 1976; Keays et al. 1981, 1982),
- Subsolidus diffusion (Naldrett & Kullerud 1967; Hoffman et al. 1979),
- Fractionation of PGE from the sulphide melt into monosulphide solid solution (MSS) (Distler et al. 1977; Malevskiy et al. 1977; Naldrett et al. 1982)
- Preferential partition of Pt, Pd and Au into a high-temperature Cu-rich sulphide liquid. That such a liquid can exist was suggested by Hawley (1962) and demonstrated by Craig & Kullerud (1969).

The data for the three deposits shown on Fig. 3d are inconsistent with the first of these explanations being the sole reason for the Cu>>Ni parageneses in that the process resulting in this type of mineralization has not only a marked effect on the Au content but has also a systematic effect at the other end of the spectrum in that the ratio (PGE)Cu>>Ni/(PGE)Ni-Cu shows an increase from Os to Ir, Ir to Ru and Ru to Au for Flåt and Hosanger. The data available from Ertelien are also consistent with this pattern. The conclusion must be that the process causing formation of the Cu>>Ni mineralization has affected all the PGE + Au in a systematic manner and that any additional effect due to hydrothermal alteration has not disturbed the resulting pattern. A more detailed study of the mineralogy and field relationships of these ores than has been possible in this project would be required before drawing any further conclusions on which process caused the formation of the Cu>>Ni mineralization but we feel that the last explanation is the most probable

4.2. Other environments in mafic intrusions.

Certain layered intrusions in Norway could be regarded as having a potential for:

a) Merensky-type Pt-Pd mineralization related to weak stratiform concentrations of Ni-Cu sulphides or

b) UG-2-type Pt-Pd mineralization related to chromite layers.

Type a) is exemplified by the Merensky Reef in the Bushveld Complex, S. Africa and by the Johns-Manville Reef in the Stillwater Complex, Montana. The Norwegian intrusion known to have the closest petrological analogies with these intrusions (crystallization orders, range of cryptic variation) is the Råna complex (Boyd & Mathiesen 1979; Boyd 1982).

The Tverrfjell portion of the Råna intrusion (Fig. 2) was selected for a detailed search for a Merensky-type deposit (Barnes 1986a, in press). This project was financed independently of the pilot project, by the Swedish mining company LKAB, NGU and NTNF. The area was mapped on a scale of 1:5000 and over 150 samples were collected along three traverses across the stratigraphy. The samples were investigated petrographically, over 2000 microprobe analyses of the minerals were made, and 146 of the samples were analysed for major and trace elements, 136 for noble metals (see Appendix 1, Table 2) and 46 for REE.

The principle conclusions of the study were as follows:
No noble metal deposit was found in this portion of the intrusion. The highest Pt values obtained were 30-50 ppb, the average was 6 ppb. As in the case of Bruvann, if the analyses are recalculated to 100 % sulphide, the calculated sulphides are depleted in PGE relative to Ni and Cu. The whole rock compositions at Bruvann, Tverrfjell and Eiterdalen are anomalous in terms of high Cu/Ir (447-2380 x 1000) and Ni/Ir (2795-13333 x 1000) ratios. Similarily the Cu/Pd (84-214 x 1000) and Ni/Pd ratios (302-1200 x 1000) are very high compared with igneous rocks from the literature. At all localities the Ni-Cu ratios (3.5-6.3) are primitive. Pt exhibits a similar behaviour to Pd. If these ratios are the result of igneous processes, then the magma that formed the accessible parts of the intrusion was depleted in platinum group elements relative to base metals.

The whole-rock geochemistry and mineral analyses suggest that the liquid from which the Tverrfjell rocks crystallized was a primitive olivine tholeiite with a MgO content of the order of 12 %. The initial liquid has affinities with E-MORB or ocean-island tholeiites. One possible reason for the unusual base to PGE ratios at Råna is that the mantle which melted to produce the Råna magma was depleted in platinum metals by a previous melting event. The initial liquid at Råna was not depleted, however, in highly incompatible elements such as Cs, Rb and LREE and therefore it seems unlikely that it was derived from depleted mantle. However, this hypothesis cannot be ruled out entirely because the exact nature of E-MORB is still a controversial subject.

A single stage partial melting of primitive mantle could not produce such high base to PGE ratios and the restite of such an event would have lower base to PGE ratios than primitive mantle, therefore melting of depleted mantle will not produce a magma with high base metal/PGE ratios.

Cu, Pt, Pd and Au are not incorporated into silicate minerals to any significant degree and silicate crystal fractionation will not change the Cu to Pt, Pd or Au ratios. Sulphide accumulation decreases the base to noble metal ratios, therefore cumulate processes in primitive magma will not produce rocks with high base to noble metal ratios. However, removal of a small amount of sulphide prior to the emplacement of batches of magma would increase the base metal to PGE ratios in the silicate melt sufficiently to generate rocks similar to those observed. In order to account for the base metal/PGE ratios observed at Tverrfjell, sulphide and olivine fractionation prior to separation and emplacement of the magmas from which these rocks crystallized is necessary.

No process-oriented study of this type has been possible within the context of the pilot project. The only samples from a comparable environment analyzed here were six samples of olivine and olivine-clinopyroxene cumulates, all containing traces of sulphide, from the tholeiitic Lille Kufjord Intrusion (Fig. 1) (Robins & Gardner 1975) on the SW part of Seiland in N. Norway). The Lille Kufjord layered gabbro is a synorogenic intrusion emplaced at a late stage in the Caledonian (Finnmarkian) evolution of the Seiland Petrographic Province. The intrusion displays a subalkaline layered sequence some 1,400 m thick preserved within an envelope of congelation cumulates up to 104 m wide developed along its steeply-dipping walls (Robins and Gardner 1974). The Lower zone of the exposed layered sequence contains cyclic units up to 50 m thick, which, when completely developed, contain olivine cumulates passing upwards into olivine-clinopyroxene cumulates and plagioclase-clinopyroxene-olivine cumulates.

Six samples were analyzed. Five were below detection limits for Os (< 2 ppb), Ru (< 10 ppb), Rh (< 1 ppb), Pt (< 10 ppb) and Pd (< 10 ppb) while all gave values for Ir (ave. 0.12 ppb) and Au (3.2 ppb) and one gave values for Rh (2 ppb), Pt (10 ppb) and Pd (13 ppb). The Pd/Ir ratio (10) and Cu/Cu+Ni ratio (0.16) of this sample indicate a weakly fractionated parent. The results do not indicate a need for further work in this intrusion.

The ony other study in a complex of this type and with a Merensky or UG2-type of target, has been carried out by industry in the Fongen-Hyllingen Complex, 65 km SE of Trondheim, which has been thoroughly studied by Wilson and coworkers (Wilson et al. 1981). The results of this study are not known.

Other intrusions which could possibly have potential for this type of mineralization include the Jotun complex, several intrusions in the Seiland area in addition to Lille Kufjord and Proterozoic chromite-bearing mafic/ultramafic intrusions in the Raipas Supergroup of West Finnmark, N. Norway.

4.3. Komatiites

Twenty-six samples of komatiite from Finnmark (Fig. 1) (from the Karasjok Greenstone Belt at c. 25^{o}E) and three from Skjomen (Fig. 1) (SE of Narvik at 68^{o}30'N) have been analyzed (Appendix 1, Table 2).

The early Proterozoic Karasjok Greenstone Belt (KGB) in the north-western part of the Baltic shield underlies the eastern part of the generally flat Finnmarksvidda, North Norway. This N-S trending greenstone belt is 160 km long and up to 40km wide. To the north,near Lakselv,the belt is overlain by autochthonous Vendian to Cambrian sediments of the Dividal group and by Caledonian nappes. The southern continuation into Finland, called the Kittila greenstone complex extends another 150km towards the south-southeast, i.e. a total length of c.300km. The Karasjok Greenstone Belt has recently been described by Often (1985).

The central part of the Karasjok Greenstone Belt ,the Bakkilvarri Formation, is a monotonous sequence of mafic volcanic rocks with an ultramafic volcanic unit(komatiite) in the central to upper part. The principal rock types are foliated to schistose amphibolites, mostly garnet-bearing, sometimes banded with felsic or graphitic material, and sometimes massive with grain size from fine to coarse. These rocks are interpreted as tholeiitic basaltic lavas, tuffs and tuffites with an unknown amount of dykes and sills. Primary structures are very scarce, but Henriksen (1983) reported pillows in a few localities.

Apple-green chlorite-amphibole rocks in the Karasjok Greenstone Belt have earlier been denoted as chlorization zones within the amphibolites (Crowder 1959), but it is now clear that they constitute an important group of rocks with komatiitic affinity which both petrologically and genetically must be distinguished from the amphibolites (Henriksen 1983). They consist mainly of magnesian chlorite and actinolite, an entirely metamorphic assemblage. The geochemistry and extrusive character of these rocks are diagnostic of komatiites as proposed by Arndt & Nisbet (1982). Their composition is in the range 35-46 % SiO_2, 18-37 % MgO, 3-8 % Al_2O_3 and 1-12 % CaO. Primary structures are surprisingly common, showing a dominance of pyroclastics with grain size from fine tuff to breccia/conglomerate. Volcaniclastic ultramafic rocks are very rare and few description exist from other parts of the world. Where known, such rocks constitute only minor parts of volcanic sequences (Gélinas et al. 1977, Nisbet et al. 1977, Nisbet & Chinner 1981). Manganese-bearing banded iron formations of Algoma type (Gross 1983) are associated with the komatiites. Sulphide chemical precipitates are found as lateral extensions of the iron formations and as layers within the pile of mafic volcanites. A Sm-Nd whole-rock errorchron has been obtained from the komatiites (Krill et al. 1985) giving an Early Proterozoic age, 2085 ± 85 Ma.

Au has been found in the glacial deposits of Finnmark and large areas of these deposits have anomalously high values of Au; Keays et al. (1982) have suggested that Au is frequently mobilized from komatiites in greenstone belts to form Au deposits and that noble element patterns from areas where this has occurred will have negative Au anomalies. Further, the komatiites of the Finnmark area are pyroclastic which is extremely unusual for komatiites, since this rock type is usually regarded as having been too fluid to form pyroclastics. One possible explanation for their pyroclastic nature could be that these komatiites are evolved (i.e. pyroxenitic komatiites) and hence are more viscous than more primitive (i.e. peridotitic komatiites. Peridotitic komatiites usually have relatively unfractionated PGE patterns with Pd/Ir ratios of 5 to 10. In contrast pyroxenetic komatiites have fractionated patterns and Pd/Ir ratios > 20 (Barnes et al. 1985).

The 26 komatiites analyzed from the Karasjok Greenstone Belt (Appendix 1, Table 2) are taken from localities within 6 different map sheets,no.2033 1-4 , 2034 2 and 4 (see Plate 1). They are mostly from the Bakkilvarri Formation, but some have been collected from units lower down in the stratigraphy. Both highly-deformed, schistose and carbonatized samples and samples with well-preserved pyroclastic and pillow structures were collected.

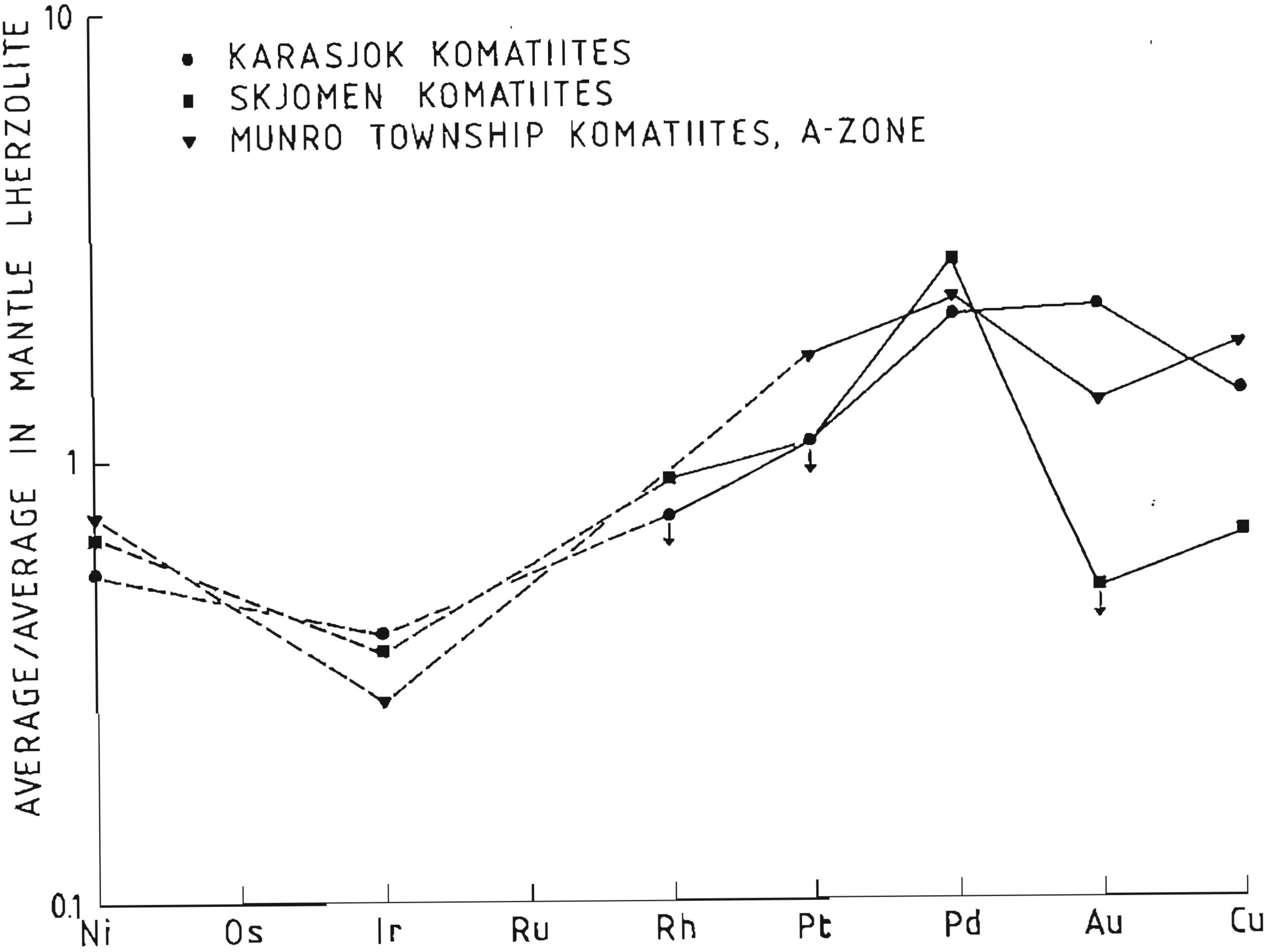

Fig. 4. Mantle-normalized average absolute concentrations of Ni, PGE, Au and Cu in komatiites from Karasjok, Skjomen and Munro Township. Data from Munro Township are from Mac Rae (1982).

The average noble element pattern does not have a negative Au anomaly (Fig. 4), which suggests that Au has not been mobilized from these rocks However, indiviual samples do show Au anomalies and local Au mobilization is possible. The noble element pattern is relatively unfractionated, with a Pd/Ir ratio of 5.8 and the pattern closely resembles noble element patterns from spinifex-textured zones of peridotitic komatiites from Canada and Australia (Fig. 4). These rocks formed from liquids which were relatively rich in PGE. However, the processes involved in the formation of pyroclastic rocks do not lead to concentration of PGE and the pyroclastics themselves are not suitable hosts for PGE deposits. If intrusive komatiites are found in the area these could have potential for PGE.

Certain ultramafic rocks from the Skjomen area, SE of Narvik, are believed to be komatiites. The Skjomen area is under investigation for gold mineralization and on the basis of the theory of Keays et al. (1982) mentioned above, 5 samples of possible komatiites were submitted for analysis. Only three of these contained PGE at levels greater than detection limit. The average noble element pattern for these three samples does have a negative Au anomaly and may indicate that Au has been mobilized from these rocks. The level and shape of the noble element pattern is similar to that observed in peridotitic komatiites from Canada (Fig. 4).

Apart from one sample, from Finnmark with 82 ppb Au, the contents of PGE and Au are low in all the komatiites analyzed - none exceeded the detection limit of 10 ppb for Ru and only two exceeded the detection limit of 10 ppb for Pt. The majority of samples exceeded the detection limits for Au (0.5 ppb) and Ir (0.2 ppb).

4.4. Ophiolites and related rocks

Platinum metals occur in association with both Ni-Cu sulphide mineralizations (see above) and chromitites in ophiolites. The recent discoveries of high PGE contents in podiform chromitites in the Shetland ophiolite (Prichard et al. 1981; Prichard et al. 1986), the Tocantins complex, Brazil (White et al. 1971), Ray-Iz (Khvostova et al. 1976) and Kempirsay (Khvostova et al. 1976) ophiolites have stimulated interest in this environment. In this project two types of chromite-bearing ultramafic rock of ophiolite kindred have been sampled. These are:

- chromite-bearing olivine cumulates from the Leka ophiolite (Fig. 1)
- chromite-bearing metaharzburgites and chromitites from isolated ultramafic bodies of probable ophiolitic affinity (Fig. 1).

PGE in olivine-chromite cumulates in the Leka Ophiolite.

A number of ophiolite fragments are present within the Upper Allochthon of the Scandinavian Caledonides. The most complete of these occurs on the island of Leka, 200 km N of Trondheim (Prestvik 1980; Furnes et al. 1980). The Leka Ophiolite Complex (LOC) (Fig. 5) has, at its base, a strongly deformed harzburgite unit, interpreted to represent the upper part of a depleted mantle. This unit becomes progressively richer in olivine towards a sequence of ultramafic cumulates, discordantly overlying the harzburgite tectonite. The cumulates are dominated by dunite and wehrlite showing the crystallization sequence: olivine-chromite-clinopyroxene-orthopyroxene.

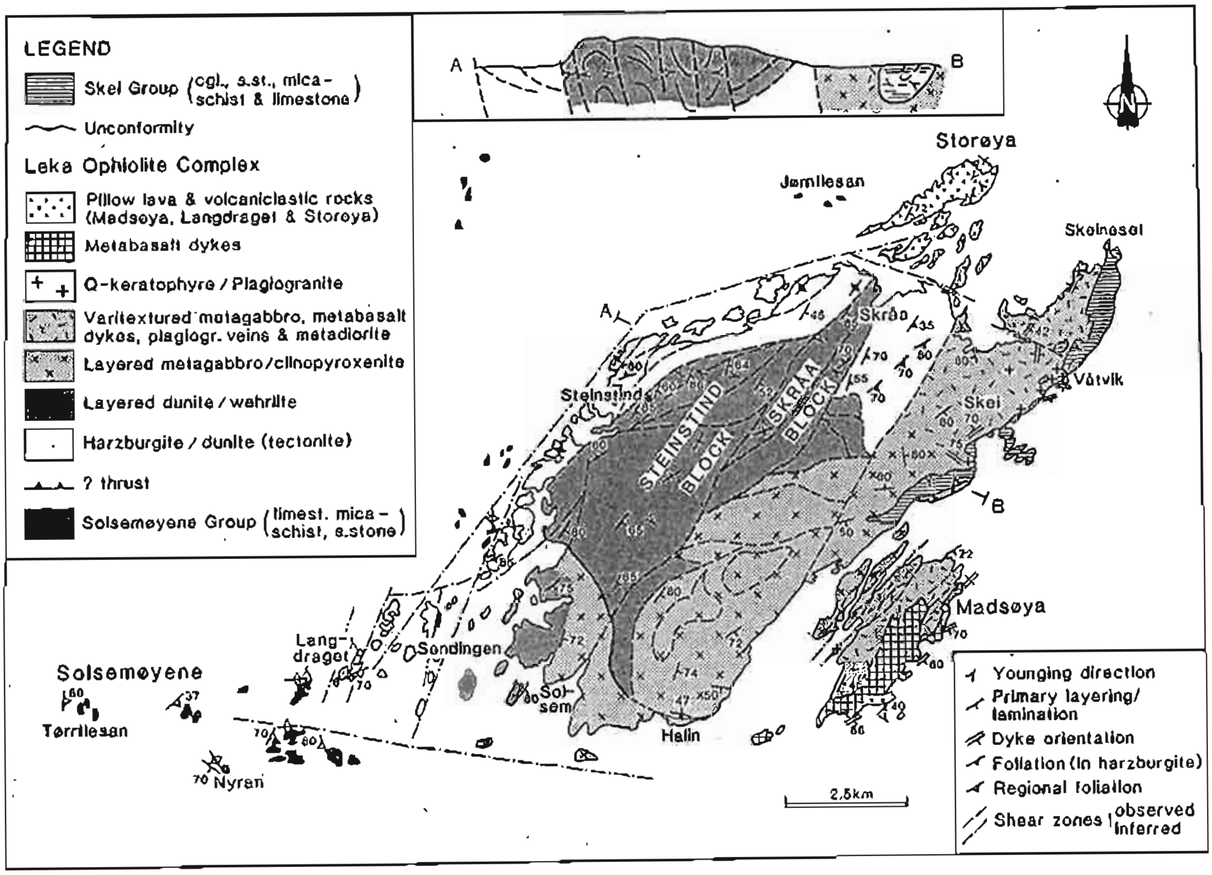

Fig. 5. Geology of the Leka Ophiolite Complex.

In the southwestern part of the ultramafic cumulate sequence, layers of gabbro are interlayered with banded dunite/wehrlite. Either of the above mentioned rock sequences may be in tectonic contact with layered gabbros which give way upwards to a laminated and varitextured gabbro. The first appearance of metabasalt dykes occurs in laminated/ varitextured gabbro, and these increase upwards in abundance from scattered single dykes to a 100 % sheeted dyke swarm. Associated with the varitextured gabbro is also a series of minor acid intrusions, which have yielded a U/Pb zircon age of 497 ± 2 Ma. Pillow lavas appear within the upper part of the dyke swarm, and at apparently higher stratigraphic levels such lavas are associated with volcaniclastic metasediments.

Geochemically the metabasalt dykes and associated pillow lavas resemble IAT and MORB, and metaboninites are also present. This geochemical association, as well as the crystallization sequence of the cumulates, strongly suggest that the first stages in the formation of the LOC was by spreading above a subduction zone. The pillow lavas associated with volcaniclastic rocks, are of MORB to WPB type, and these probably represent the later evolution of the LOC in a back-arc basin, but at sufficient distance to be unaffected by the geochemical "fingerprints" of the subduction process.

The samples analysed for PGE (for results see Appendix 1, Table 2) were collected in the ultramafic <u>cumulate</u> section. The sequence consists of thick layers (on the 100 meters scale) dominated by either dunite or wehrlite. Superimposed on these are macrocyclic units (on the 10 meter scale). The macrocyclic units exhibit dunite at the base which locally may be enriched in chromite. Clinopyroxene becomes gradationally more abundant upwards, forming wehrlites. The macrocyclic units are also defined by compositional variations in olivine (Fig. 6). At the base of the macrocyclic units olivine compositions change abruptly from Fo 86-87 to Fo 91-93 followed by a gradational decrease in Fo content towards the top of the units.

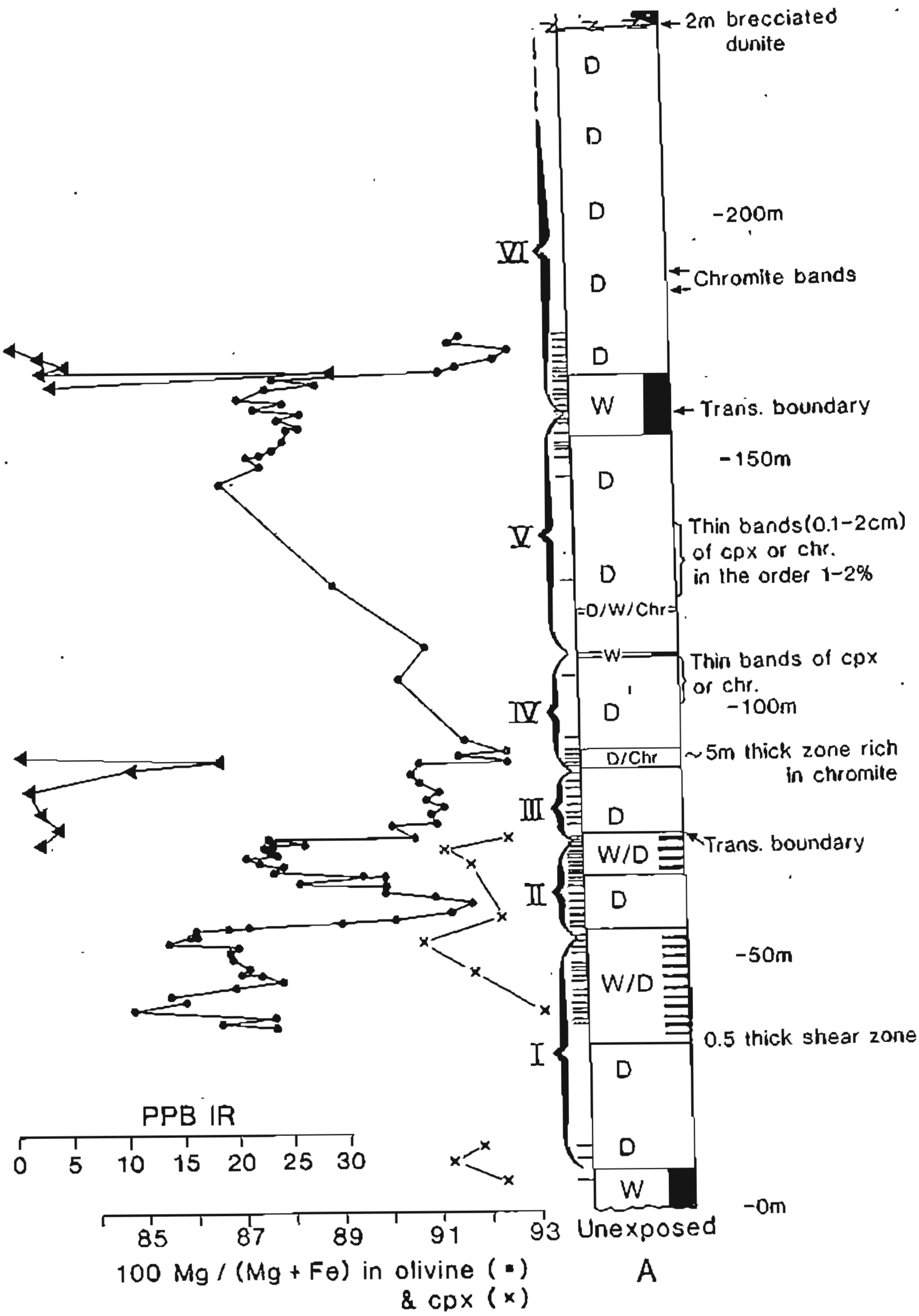

Fig. 6. Stratigraphy of ultramafic cumulates in the Leka Ophiolite Complex.

The macrocyclic units are interpreted to have formed by the influx and subsequent fractionation of a very magnesian parental magma (MgO > 20 wt%). If this is the case, the large scale olivine-rich layers may represent periods with a high frequency of such influxes while the more wherlitic layers formed when the total influx was lower, or the magma had gone through more fractionation before entering the magma chamber.

Most of the samples analysed, which were not particularly chosen because of enrichment in chromite, were collected systematically from the lower parts of three macrocyclic units within a dunitic large-scale layer (Fig. 6). While Ir shows a marked enrichment at the base of two of these units (units IV & VI), no such enrichment is observed at the base of the third unit (unit III). However, since the enrichments in units IV and VI are limited to a maximum section of 2 meters, the apparant lack of enrichment in unit III may be explained by sample spacing. The picture described above is also partly reflected by Os and Ru. Three samples of chromite-bearing dunite, collected unsystematically from the lower levels of similar cyclic units, were analysed to see if any high concentrations of platinum group elements could be encountered within this rock suite. While two of these samples show abundances similar to the above rocks, the third sample was enriched, exhibiting 3600 ppb of Os-Ir-Ru. The compositional variations of these samples together with the general petrogenetic model of the layered sequence, suggest that the parental magma precipitated phases enriched in Os-Ir-Ru just after it entered the intracrustal magma chamber.

The enriched sample (81.1.L, Table 2) exhibits a typical Os-Ir-enriched chromitite pattern (Fig. 7): the level is higher than the average chromitite, but similar to values obtained for Harold's Grave in the Shetland ophiolite (Gunn et al. 1985) or chromites from New Caledonia (Page et al. 1982). These high values are usually associated with inclusions of Os-Ir alloys and RvS_2 (laurite), on which the chromite may orginally have nucleated. The remaining Leka samples contain noble metal levels close to 1 to 3 times mantle level and have esentially flat metal patterns. The PGE levels are similar to those observed in the dunite from the Thetford ophiolite of Quebec (Oshin & Crocket 1982). These rocks are cumulates and therefore the unfractionated nature of the PGE distribution is not simply the result of sampling mantle-related rocks, but probably represents the sum of a chromite pattern and a sulphide pattern diluted by cumulus minerals.

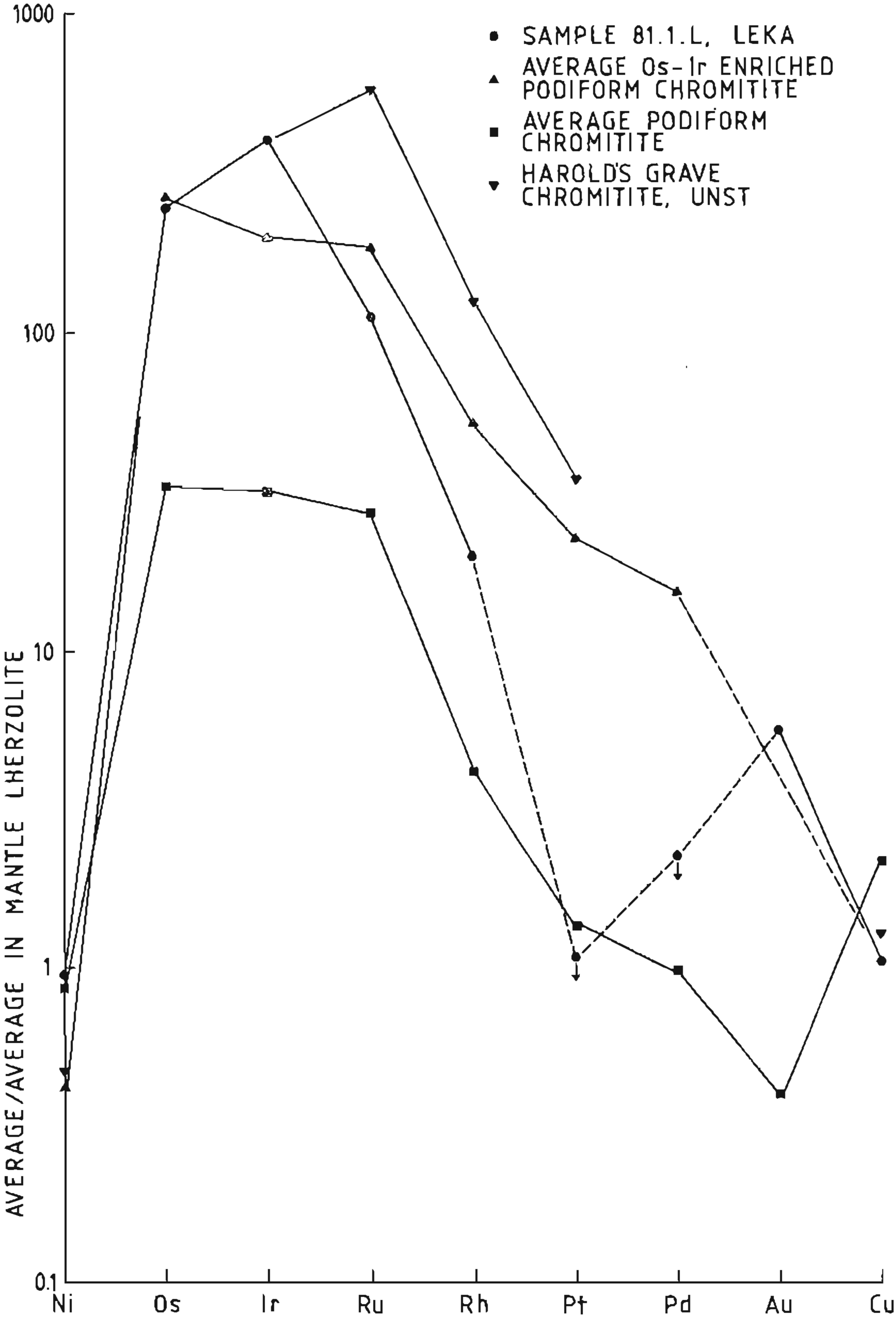

Fig. 7. Mantle-normalized absolute concentrations of Ni, PGE, Au and Cu in chromitites. The two average profiles are compiled from a range of sources and the data from Unst are from Gunn et al. (1985).

PGE in isolated ultramafic bodies: South-central Norway.

The greatest concentration of chrome-ore bearing ultramafic bodies in Norway are the isolated ophiolite fragments found in a single nappe unit of the Caledonian tectonostratigraphy in the south-central part of the country, S of Trondheim (Stigh 1979). This nappe has different local names in different areas, but from east to west across central Norway it has been called the Essandsjø Nappe, Bottheim Group, Blåhø Nappe, etc. These nappes are thought to correlate with the Seve Nappe in Sweden, and all of them are presently regarded as the lowermost unit in the Upper Allochthon (Gee et al. 1985).

Chrome-ore bearing ultramafites in regions outside central Norway are found in the Upper and Uppermost Allochton in Nord-Trøndelag and in the Helgeland coastal area in north-central Norway. It is possible that these bodies occur in tectonic repetitions of the nappe in which the ultramafic bodies in south-central Norway are found.

Most of the chromite produced in Norway has comes from the ca. 15 km^2 Feragen body in the Essandsjø Nappe close to the Swedish border, 120 km SE of Trondheim (Fig. 1). This body consists of approximately equal amounts of dunite and harzburgite and has contributed almost 90 % of Norway's total chromite production, about 32,500 metric tons (Poulsen 1960). The major part of the ore was produced in four mines: the Skal, Rødtjern, Leigh and Ler mines. All four mines produced a range of ore types, including compact ore, leopard ore/pique-ore, schlieren-impregnated ore, fine-banded ore, and fine-grained, disseminated ore. All the ores satisfied the requirements of chemical-grade ore, typically having high Cr-values and low Fe-values. In addition, all ore types show only a slight alteration to secondary iron-rich chrome-oxides (ferritchromite and chrome-magnetite).

Twenty-four samples from the Feragen area were analyzed for PGE. None showed PGE-values (Pt and Pd) significantly over analytical detection levels. A further 32 samples from other smaller chromite-bearing ultramafic bodies in the Essandsjø Nappe in S. Central Norway were analyzed. Four of these have (Pt + Pd) > 100 ppb.

Sample LP 32 with 760 ppb Pt and 8 ppb Au was collected from the Osthammeren ultramafite a 0.1 km^2 serpentinized dunite body located approximately 15 km west of the Feragen body. The ore-sample was collected from compact chromite-ore in one of five small claims situated along a line running east-west across the top of the dunite outcrop. Petrographic inspection of three polished sections of the ore-sample indicates that chromite is deformed by a weak cataclastic fabric, and that it has only slight ferrite-chromite alteration along cracks and grain boundaries. There are also numerous pale yellow awaruite grains in the serpentine and chlorite gangue, and between the chromite grains. The appearance of awaruite is characteristic of the Feragen and neighbouring sulphur-poor ultramafic bodies.

Within the chromite grains in the Osthammeren ultramafite there are a number of small, grey-white, irregular inclusions having very high reflectance similar to that of awaruite (e.g. 70 - 75 %). These inclusions were analyzed by electron microprobe (by L.P. Nilsson) and found to be mainly Os-, Ir- and Ru-rich phases with minor Pt-rich phases (e.g. sperrylite). The minerals found to date are Os-laurite $(Ru,Os,Ir)S_2$; laurite RuS_2; sperrylite, $PtAs_2$; irarsite, IrAsS; iridosmine, (Os,Ir) alloy, an unnamed mineral, IrSbS, characterized as UN 1976-11 by Cabri (1981) and an unnamed Ir-Pt-Pb sulphide, the formula of which is uncertain. Os-laurite, laurite, irarsite and iridosmine are recorded here for the first time in Norway (see Neumann 1985) while this is only the third known occurrence of IrSbS (Cabri 1981); The first record describes the mineral as small inclusions in Pt-Fe alloys in placers from the Tulameen River, British Columbia and from Colombia (Raicevic & Cabri 1976). The paragenesis as recorded so far, is similar to that in the chromitite from the Vourinos ophiolite (Auge 1984). The Pt content in sample LP 32 from Osthammeren is 760 ppb. Microprobe-analyses of inclusions (single grains and grain aggregates) carried out to date have revealed that Pt is absent, or is only a minor component in most of these inclusions whereas Ir, Os and Ru are the main PGE present. These elements could not be determined because of analytical problems. The total PGE-level is therefore considered to be several times higher than the Pt level ie, somewhere on the order of 5-10 ppm.

The other PGE-rich samples from S. Central Norway (LP 42 and LP 43) come from the Aurtand (9^{o}6'E, 62^{o}15'N) (LP 48), and Skamsdalen (8^{o}55E, 62^{o}9'N).

mines in the Lesja district in Gudbrandsdalen. The regional metamorphic grade is higher in this area than in the Feragen-Osthammeren area, producing a talc-magnesite-tremolite-metamorphic olivine assemblage in many of the host ultramafites.

The Skamsdalen ore-type is a compact ore affected little by secondary alteration whereas the Aurtand ore type is gradational between disseminated and compact ore, often containing chromite in fine bands and clusters. In addition, the Aurtand sample is nearly totally altered to ferrite-chromite. In a polished section of sample LP 43 from the Skamsdalen mine, a few, very small, gold-like grains were observed. These grains are clearly different from the grey-white Osthammeren inclusions (sample LP 32) and may, according to the Au + PGE-analysis, be a Pd-Pt-Au alloy where Pd and Au are in equal abundance.

Two polished sections of the Aurtand sample (LP 48) showed various types of small inclsions in the silicates and between the altered chromite grains. These small grains (c. 1 - 5) have gold-like, silver-like and native copper-like colours, and very high reflectance values. The high-reflectance grains in these samples will be analyzed by electron microprobe.

PGE in isolated ultramafic bodies: Helgeland, N. Norway

The samples analyzed came from the Rødøy - Melfjord area om N. Helgeland and from Velfjord in S. Helgeland. Approximately 30 ultramafic bodies are known in the North Helgeland area. The bodies consist of metaperidotite of generally harzburgitic composition with chrome spinel as a common accessory mineral. Chromite also occurs as 1 dm - ½ m thick lenses and stocks of massive chromitite. The lensoid bodies, conformably enclosed within high-grade mica schists or paragneisses, are from 50 m to 1.5 km long. The larger bodies may show a zonal structure with a dunitic core surrounded by massive olivine orthopyroxenite.

Seven chromite samples have been analyzed for PGE. Of these one sample from the Ørnstolen ultramafic body (13°E, 66°36'N) showed highly anomalous values (718 ppb Au, 299 ppb Pt, 1391 ppb Pd). Other samples contained <200 ppb (Pt+Pd+Au).

The Ørnstolen ultramafic body crops out over an area of c. 200 x 200 m. It is a typical metaperidotite, composed of olivine + orthopyroxene ± talc ± carbonate as the main minerals. The total amount of chromite is probably less than 5 vol. %, though 1-5 m thick zones may have 10-20 vol. % disseminated chromite. Chromite also occurs typically in 1-3 dm thick "fragments" or lenses irregularly distributed in the ultramafic body. The Ørnstolen body is one of the most chromite-rich of North-Helgeland, and the only one which shows relicts of a layered sequence of disseminated chromite.

As with the Osthammaren sample it is possible that Pt and Pd are not the dominant PGE in the anomalous samples from Helgeland. Further bulk chemical and mineralogical work is in progress to assess this possibility.

4.5. Alaskan type ultramafic intrusions

Four intrusions in the Seiland Province of N. Norway (Melkvann, Nordre Bummansfjord, Kvalfjord and Reinfjord) (Bennett et al. 1986) are known to have petrological features in common with the Alaskan-type intrusions as described by Irvine (1974). All four show emplacement of ultramafic complexes into earlier layered mafic intrusions, an evolution in which successive pulses of magma have a diminishing number of liquidus phases, each also showing in-situ liquid-crystal fractionation (Bennett et al. 1986). Bodies of this type are the source of placer PGE deposits (Pt - Ir - Os) in the Urals, Alaska and British Columbia (Razin 1976; Cabri 1981: Cabri & Naldrett 1984). The PGE are associated with chromite in the ultramafic cores. Twelve samples from the Melkvann Complex and nine from Reinfjord were analyzed.

The Melkvann complex (Fig. 8) occupies an area of some 100 km^2 in the southern part of the island of Seiland and is emplaced into a formerly extensive layered olivine gabbro, the remnants of which are preserved in places around the margins of the complex, and as enclaves within it. The body lies in the core of a large doubly-plunging synform, the southern closure of which is locally overturned. The ultramafic rocks lack a systematic penetrative foliation, the most conspicuous structural element within the complex being a prominent set of steeply northerly-dipping joints.

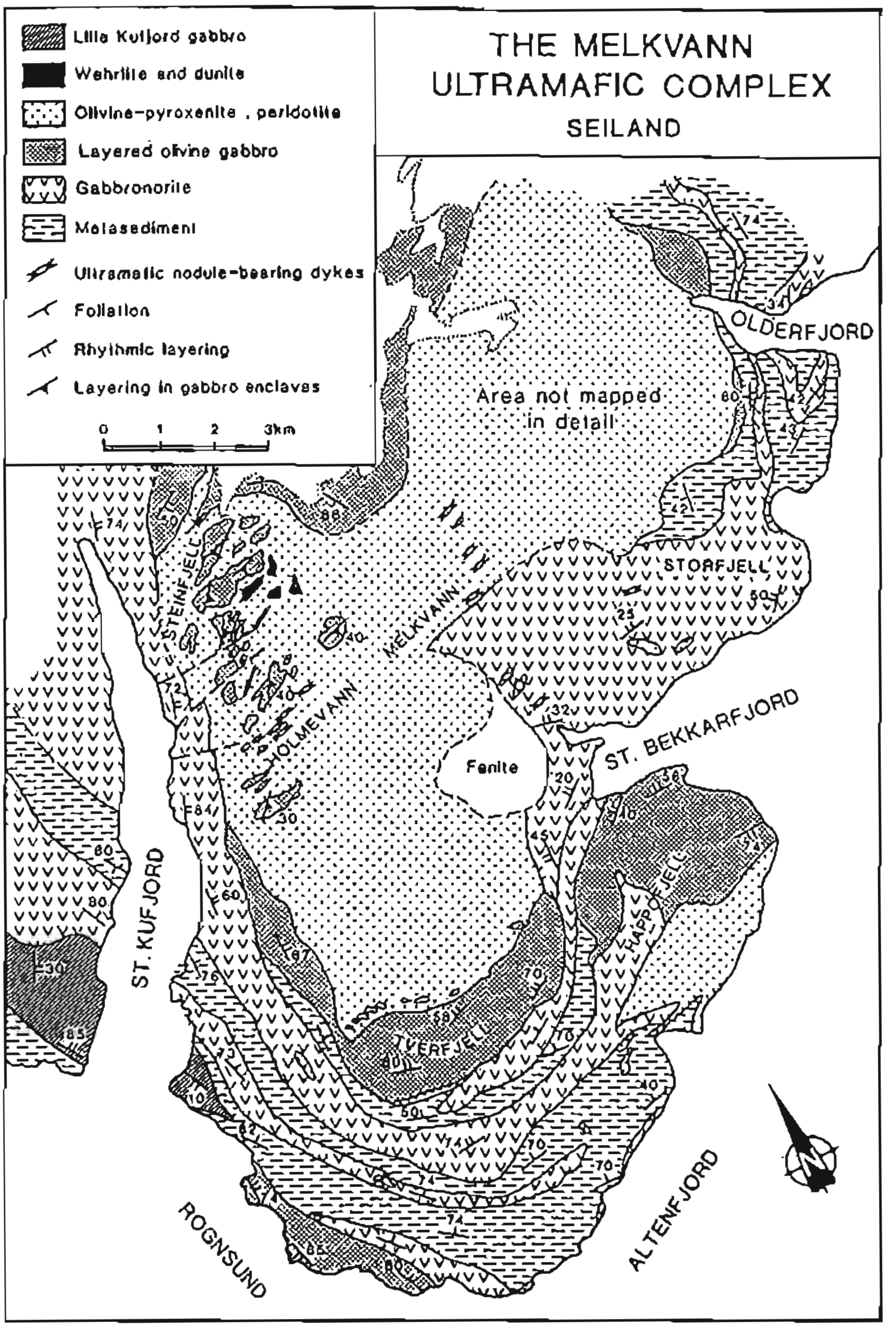

Fig. 8. Simplified geological map of the Melkvann ultramafic complex and its envelope (from Bennett et al. 1986).

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

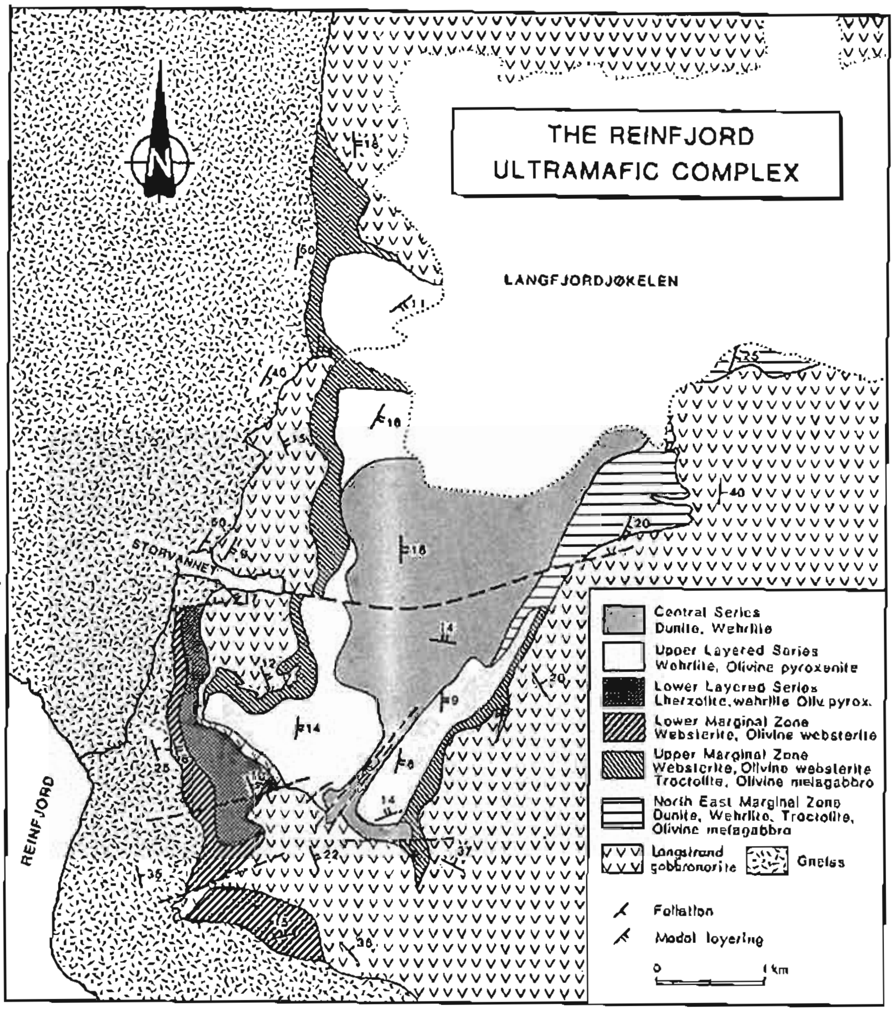

Fig. 9. Simplified geological map of the Reinfjord ultramafic complex and its envelope (Bennett et al. 1986).

The Reinfjord complex (Fig. 9) lies some 50 km southwest of Seiland and Stjernøy and although of comparable age differs from the other high-temperature ultramafic complexes in two important respects. Firstly, the Reinfjord complex contains extensively developed layering together with a crudely concentric modal and cryptic variation. Secondly, it is emplaced into a layered gabbro of subalkaline character (the Langstrand gabbronorite), and to some extent this is shared by the ultramafic cumulates themselves.

The exposed part of the Reinfjord ultramafic complex contains two early layered series, one structurally above the other and separated by a sub-concordant screen of gabbro that projects from the envelope into the southwestern corner of the complex. The Lower Layered Series, consisting mainly of lherzolite, wehrlite and olivine clinopyroxenite, is restricted to a level below the gabbro screen and is exposed only in the southwestern corner of the complex. The Upper Layered Series, consisting of wehrlite and olivine clinopyroxenite, has a more extensive outcrop above the gabbro screen, and forms a plateau 550-800 m a.s.l. Both series pass laterally through transitions of variable width into marginal zones dominated by websterite and olivine websterite, but also containing smaller volumes of olivine melagabbro and troctolite, spatially associated with numerous gabbroic xenoliths in various stages of assimilation, and blocks of coarse-grained pyroxenite. In the central part of the complex, an extensive outcrop of dunite and subsidiary poikilitic wehrlite represents a later phase of intrusion. Towards the eastern and western margins of the complex, this later body is grossly discordant and cuts both the Upper Layered Series and its time-equivalent Upper Marginal Zone. Towards the south, it extends as a relatively narrow tongue to the southern margin of the complex, forming a steep-sided, dyke-like body, 100-200 m wide. Extrapolation of outcrop data suggests that the Reinfjord complex approximates to a crudely elliptical cylindroid plunging very steeply in a northeasterly direction. Contacts with its envelope are strongly discordant, being either near vertical or steeply inclined to the northeast or east.

The analysed samples from Melkvann are all below detection level for Rh (1 ppb) (Appendix 1, Table 2) and Ru (10 ppb) and in two cases only reach the detection level for Os. The remaining elements show Ir = 0.6 ppb, Pt < 7.3 ppb, Pd < 6.5 ppb, Au = 1.4 ppb. It should be noted that none of these samples are chromite-bearing. The levels of Pt and Pd are c. 20 % of the average shown for all Alaskan-type complexes (St. Louis et al. 1986). The average of three samples from the Upper Layered series at Reinfjord is similar to the overall average at Melkvann. Other samples give lower values. There is no indication of PGE potential on the basis of these data, but if chromite-bearing dunites were discovered in any of the intrusions these should be studied for PGE.

4.6. Other potential environments

The only remaining samples analyzed were 17 eclogite samples from Åheim. The average values were less than detection levels for all elements, except Au which was 2.7 ppb (Appendix 1, Table 2). The average of the 4 samples greater than detection limit is close to mantle values, indicating possible mantle derivation for these 4 samples.

5. CONCLUSIONS

A considerable amount of data has been accumulated in the course of the pilot project, much of it of scientific interest. Results from only one of the geotopes sampled, ophiolites and related rocks, give an indication of possible economic interest. The specific targets located so far considered to merit further study are:

- chromite-olivine cumulates in the Leka ophiolite
- chromite-bearing harzburgites forming isolated ultramafic bodies ie. Osthammaren, Skamsdalen, Aurtand and Ørnstølen.
- the potential for further Cu-Ni-PGE mineralizations of the Fæøy type in the Karmøy ophiolite

Critical topics to be examined in the Leka ophiolite will be the lateral and vertical extent of Os-Ir-Ru enrichment, geochemical variation within the enriched zone, the mineralogical residence of the PGE and the processes leading to their concentration.

In the isolated harzburgitic bodies the critical question in an economic evaluation will be whether the PGE are exclusively linked to chromite. All the chromite mineralizations found to date are very small. Similar problems to those indicated above will have to be studied should it prove that some of the PGE have a broader occurrence. These problems have otherwise a considerable scientific interest.

The pilot project permitted analysis of samples from only a few of the potential targets of this type. Others would certainly also have revealed anomalous values and a more thorough inventory should be considered.

In the other geotopes examined, further PGE studies with an economic goal should be conditional on the identification of more 'prospective' targets, eg. sulphide-bearing komatiites, intrusives of komatiitic parentage, chromite-bearing dunites in the Seiland Province.

Two possible geotopes remain to be sampled. These are the cover sequences overlying ophiolites, where these is a potential for fossil placers, and black shales. At least in the first case it should be possible to use Cr as an indicator for PGE.

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APPENDIX

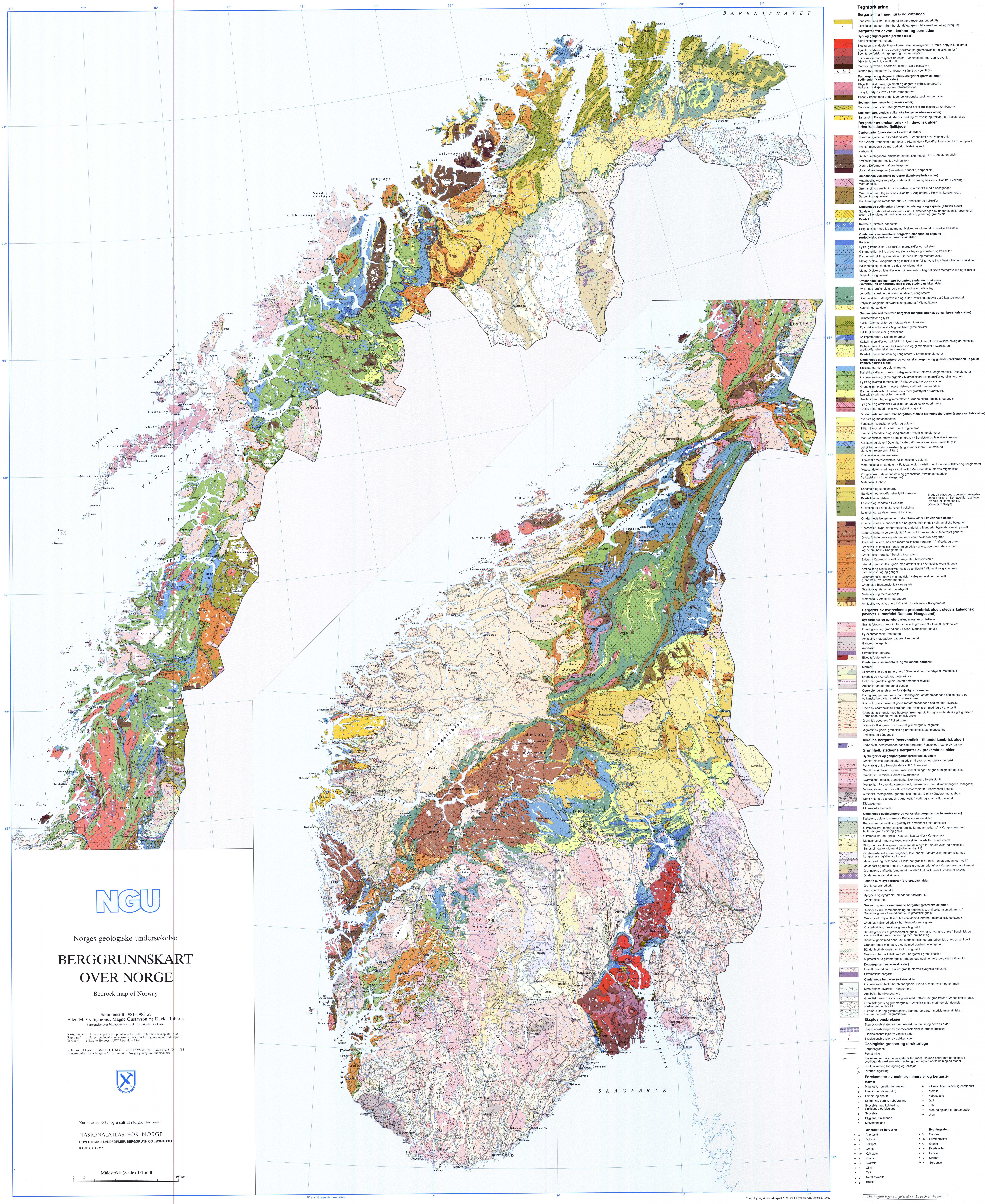
	Coord-inates	AGE	METRIC TONS METAL x 10^3 Ni	METRIC TONS METAL x 10^3 Cu	AVE. GRADE % Ni	AVE. GRADE % Cu	MAJOR SULPHIDES	TRACE MINERALS INCL. KNOWN PGM	% Ni, Cu, ppb PGE + Au CONTENT IN 100 % SULPHIDE Ni	Cu	Os	Ir	Ru	Rh	Pt	Pd	Au	Cu/ Cu+Ni	Pd/ Ir	n
BRUVANN 1)	16°58'E 68°20'N	L.P.	142	34	0.32	0.08	po,pn,cp,py	arsenopyrite gersdorffite niccolite molybdenite sphalerite No known PGM	9.0	2.1	-	6	-	-	52	70	1010	0.19	11.3	10
SKJÆKERDALEN	12°11'E 63°51'N	L.P.	2.2	1.1	0.22	0.11	po,pn,cp	bravoite linnaeite PGM not studied	3.1	2.7	-	-	-	-	100	721	536	0.67	-	7
VAKKERLIEN 2)	10°17'E 62°32'E	L.P.	4	1.6	1.0	0.4	po,pn,cp,py	gersdorffite violarite no known PGM	10.9	2.2	39	51	62	42	788	350	49	0.16	6.8	6
HOSANGER Ni-Cu	5°31'E 60°32'N	Pr	4.2	1.6	1.05	0.35	po,pn,cp,py	no data	3.2	0.4	28	21	38	7	71	105	9	0.10	5.0	7
HOSANGER Cu-Ni		Pr	-	-	-	-		"	0.6	7.7	28	23	59	-*	-*	-*	342	0.92	-	3
ESPEDALEN 3)	9°23'E 61°24'N	Pr	1	0.4	1.0	0.4	po,pn,cp	"	6.6	2.0	27	26	48	36	330	250	280	0.23	9.6	6
FLÅT Ni-Cu	7°50'E 58°35'N	Pr	19.5	12.2	0.75	0.47	py,po,pn,cp	millerite violarite no known PGM	2.9	0.6	23	29	46	11	68	82	58	0.17	28	7
FLÅT Cu-Ni		Pr	-	-	-	-		no data	0.8	7.2	15	19	53	-*	-*	-*	650	0.90	-	4
ERTELIEN Ni-Cu	10°3'E 60°3'N	Pr	4.2	2.8	1.04	0.69	po,cp,py,pn	"	2.1	0.4	7	1.7	-	9	273	184	111	0.17	108	9
ERTELIEN Cu-Ni		Pr	-	-	-	-		"	0.7	1.8	-	0.6	-	10	-*	-*	4.34	0.94	-	6
FÆØY	5°11'E 59°17'N	L.P.	0.8	1	2.1	2.63	po,cp,pn,py	kotulskite temaganite sperrylite	1.9	4.2	234	195	219	244	1794	4760	101	0.69	2.4	6
LILLEFJELLKLUMPEN 4)	13°25'E 64°43'N	L.P.	<0.1	<0.1	4.0	1.2	po,py,pn,cp	merenskyite sperrylite moncheite temagamite electrum Ag-pentlandite	4.0	1.2	139	170	189	214	1799	3068	219	0.33	18	8

Table 1: Data on PGE content and other aspects of Ni-Cu deposits mentioned in the text. -*: data unreliable bacause of analytical problems. Data also taken from following sources: 1) Boyd et al. (in press), 2) Thompson et al. (1980), 3) Naldrett et al. (1979), 4) Grønlie (in press). L.P. Lower Palaeozoic, Pr. = Proterozoic.

APPENDIX

	ppm				ppb					
	n	Ni	Cu	Co	Os	Ir	Ru	Rh	Pt	Pd	Au
Tverrfjell 1)	115	443	110	73	<2	0.06	<10	0.8	8.2	10	7.3
Lille Kufjord	6	813	206	-	<2	0.6	<10	<0.7	<6	<6	3
Finnmark komatiites 2)	26	1123	117	-	<3	2	<10	0.6	<10	<10	2
Skjomen komatiites	3	1333	19	-	<3	1.62	<10	1.8	<10	12.2	<0.75
Leka dunites	15	1980	27	-	<8.7	7.8	<26	<2.6	<10.5	<15.5	2.9
Leka, sample 81.1.L	1	1900	30	-	1070	1760	770	40	<10	<10	8
Chromitites, normal	64	1260	20	-	n.d.	n.d.	n.d.	n.d.	11.4	5	11
Osthammeren chromitite	1	1700	75	-	n.d.	n.d.	n.d.	n.d.	760	42	8
Aurtand Chromitite	1	1300	46	-	n.d.	n.d.	n.d.	n.d.	427	104	5
Skamsdalen chromitite	2	1250	11	-	n.d.	n.d.	n.d.	n.d.	133	91	62
Ørnstolen chromitite	1	1000	91	-	n.d.	n.d.	n.d.	n.d.	299	1391	718
Melkvann	12	1030	160	-	<2	0.6	<10	<1	<7.3	<6.5	1.4
Reinfjord	9	830	162	-	<2	0.46	<10	<1	<5.2	6.7	1.59
Eclogites	17	-	-	-	<5	<1	<10	<1	<10	<10	2.7

Table 2: Data on various rock types analyzed for PGE and discussed in the text n.d. = not determined. 1) Barnes 1986, 2) Barnes and Often, in preparation.



NGU

Norges geologiske undersøkelse

BERGGRUNNSKART OVER NORGE

Bedrock map of Norway

Sammenstilt 1981–1983 av
Ellen M. O. Sigmond, Magne Gustavson og David Roberts.

Fortegnelse over bidragsytere er trykt på baksiden av kartet.

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