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From genetic concepts to practice – lithogeochemical identification of Ni-Cu mineralised intrusions and localisation of the ore

by Pertti Lamberg



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FROM GENETIC CONCEPTS TO PRACTICE -LITHOGEOCHEMICAL IDENTIFICATION OF Ni-Cu MINERALISED INTRUSIONS AND LOCALISATION OF THE ORE

by

PERTTI LAMBERG

with 264 pages, 183 figures, 40 tables in the text and 1 appendix CD

ACADEMIC DISSERTATION

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The most important task of lithogeochemical Ni sulphide exploration tools has been to evaluate whether a mafic or ultramafic body under investigation had become sulphide-saturated during the magmatic stages. This has been assessed using the Ni vs. MgO, Ni vs. Cr and the Ni vs. forsterite content of olivine. Techniques analysing crustal contamination, with rare earth elements for instance, have been suggested. Although the theoretical background for the genesis of Ni sulphide deposits is well established and widely accepted, lithogeochemical exploration tools are still mainly qualitative and deserve consideration.

In order to develop tools to identify fertile, Ni-Cu mineralised targets, nine intrusions were selected for the case studies. The fertile Bruvann deposit, with 6.8 Mt ore at 0.54 wt.% Ni and 0.10 wt.% Cu, is located in Norway and is a part of the 437 Ma old Caledonian orogenic Råna intrusion. Other two fertile cases, Stormi (7.6 Mt @ 0.68 wt% Ni and 0.42 wt.% Cu) and Laukunkangas (6.7 Mt @ 0.78 wt.% Ni and 0.22 wt.% Cu), belong to 1.89-1.87 Ga Svecofennian orogenic intrusions in Finland and Sweden, as do the subeconomic Ekojoki, Rausenkulma and Rörmyrberget and the barren Posionlahti and Porrasniemi. The barren Alter do Chão is a pre- to early Hercynian intrusion in Portugal.

The fertile and subeconomic intrusions show, especially in the mineralisation, direct and indirect evidence of black schist contamination of the magma, such as partly digested black schist fragments, abundant graphite, molybdenite and anomalously high contents of vanadium and manganese. Although evidence of contamination is clear, it is too heterogeneous and localised to be used in the identification of fertile intrusions. The barren intrusions differ in two ways from the fertile and subeconomic ones: Posionlahti and Porrasniemi are Ni depleted and Alter do Chão is barren of sulphides.

Lithogeochemically, the fertile and subeconomic intrusions are similar but in the subeconomic intrusions sulphides are associated with pyroxenitic cumulates within the intrusion, not with olivine cumulates in the primary bottom areas. These features indicate that although subeconomic intrusions are formed from sulphide-saturated melts, the accumulation process has been inadequate.

Two important new parameters calculated from barren cumulates were found useful in monitoring sulphide segregation history. The Co#, 100*Co/(Co+Ni+Cu), describes whether sulphides are Ni depleted or not, and the Ni#, 100*Ni/(Ni+Cu), describes the primitiveness of the magma from which the sulphides have segregated. The calculation is reliable if sulphides are a cumulus phase, i.e. their content is higher than 0.3 wt.%. In undepleted intrusions the Co# is low, <10, in moderately depleted 10-20 and in extremely depleted >20. In primitive komatilitic and picritic systems the Ni# is greater than 75, in basaltic 50-75 and in more evolved flood basalts <50. Fractionation of olivine brings the Ni# down but the Co# remains at the same level, whereas segregation of sulphides increases the Co# significantly in the residual melt and in sulphides in equilibrium with it. In the Ni-Cu ores studied here the Co# is low, at 1-5, but it increases in the stratigraphic units above the ore. In the ultramafic Stormi intrusion the Co# range is quite narrow, at 2.9-15, but in the differentiated mafic intrusions, Laukunkangas and Bruvann, the range is as wide as 3-60. The Co# demonstrates clearly the depleted nature of Porrasniemi and Posionlahti where the lowest Co# values are 11 and 23.

On the basis of these case studies a *fertility analysis* for the identification of fertile intrusions was developed. The parameters of the *fertility analysis* quantify the requirements of the Ni-Cu sulphide ore formation and are: i) primitive character of the magma, ii) extent of sulphide saturation, iii) Ni-rich, chalcophile undepleted magma, iv) magmatic sulphides that are equilibrated with a large amount of magma, v) coeval primitiveness and sulphide segregation, vi) sulphide accumulation and vii) fractionation or mobilisation of sulphides. The value of the parameter is calculated from the whole-rock analyses of the rock samples. Mineralised samples are excluded from the fertility analysis.

The overall discrimination value, or *OD*, is calculated from these parameters. The integer gives the number of the last qualified step and the decimal place describes how well it was done, i.e. the *OD* can vary between 0.000 and 7.499. In the case study intrusions the fertility analysis is capable of discriminating between fertile (OD=5.05-7.31), subeconomic (3.39-5.04) and barren intrusions (1.49-3.20). The fertility analysis is not particularly sensitive to the number of samples and their lithology, but preferably the number of samples should be >25, and the samples should be as mafic as possible; then the accuracy of the *OD* will be ± 1 .

In the test with lithogeochemical datasets of the Svecofennian intrusions of Finland (7517 samples / from 353 targets), Thompson Ni belt, Canada (1207/31) and Cape Smith belt, Canada (287/27), the fertility analysis successfully discriminated between fertile and barren targets and, interestingly, some targets, which according to current knowledge are barren, received a high OD.

The fertility analysis is a new Ni sulphide exploration method, which gives measurable values for the key processes of Ni sulphide ore formation. It is unambiguous, can be done based on simple whole-rock analyses, gives one unambiguous number which can be used for ranking and is relatively easy to calculate and computerise. It also has potential in PGE exploration.

Key words (GeoRef Thesaurus, AGI): mineral exploration, nickel ores, copper ores, platinum ores, intrusions, igneous rocks, lithogeochemistry, sulphides, mineralogy, mineral deposits, genesis, Svecofennides, Proterozoic, Paleozoic, Finland, Sweden, Norway, Portugal

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For Tarja, Valtteri, Martti and Anni Nuuf nuuf, on nikkeliä nuf nuf, rautasuoni kulkee kohti Mikkeliä, snif.

Snif sniif, on lyijyä snif snif ja maahis-ämmä kutoo rikkikiisuryijyä maan alla, aaaatsnif kun aivastuttaa andalusiitti ja kullan kuiske kutittaa ja hopeasta housut kastuu –

ja viikon päästä tuli lopputili.

Ilpo Tiihonen: Malmikoira joka nuuski maan aarteita. In Tiihonen, I. 1991. Antero Vipuliini ja taikatakki. Gummerus Junior Oy, Helsinki, 101 p. (Courtesy of Ilpo Tiihonen)

FC	OREWOR	D	
PA	ART I: GE	NETIC CONCEPTS	
1	INTR	ODUCTION	
2	AIM	AND CONTENT OF THE STUDY	
3	GEN	ETIC CONCEPTS	
	3.1	Primitive character of magma	
	3.2	Sulphide saturation	
	3.2.1	Crustal contamination	
	3.2.2	Identification of sulphide-saturated magmas	
	3.3	Sulphide segregation	19
	3.4	Sulphide accumulation, solidification and subsolidus re-equilibration	
	3.5	Chemical composition of sulphides – introduction of nickel and cobalt numbers	
4	MET	HODS AND TERMS	
	4.1	Sampling	
	4.2	Chemical analyses	
	4.3	Mineralogy	
	4.4	Analyses from the Nickel Programme database	
	4.5	Processing of the chemical analyses	
	4.5.1	Composition of the sulphide fraction (SF)	
	4.5.2	Nickel and cobalt numbers (Ni#, Co#)	
	4.5.3	Volatile-free (VF) and volatile- and sulphide-free (VSF) compositions	
	4.5.4	Normative mineral composition	
	4.5.5	Chemical compositions of minerals	
	4.5.6	Normative cumulus name of the rock	
_	4.6	Subdivision of intrusions	
P/	ART II: CA	ASE STUDIES	
5	INTR	ODUCTION TO THE CASE STUDIES	
	5.1	Targets	
,	5.2	Svecotennian matic-ultramatic intrusions	
6	BRU	VANN	
	6.I	Kana intrusion	
	0.1.1	Subalvision	
	0.1.2	Nielel common and	
	0.2 6.2	Nickel-copper ore	
	0.5	Dependent magnes and existent in trands	
	6.2.2	Origin of graphite and gulphur	
	6.2.2	Contamination	
	624	Sulphur saturation and shaloophilo alament doulation	
	6.4	Geological model	
7		VEOLOGICAL MODEL	
/	7 1	Geology and subdivision	
	7.1	Chemistry and mineralogy	
	7.2	Nickel_copper ore	
	7.5	Genetic considerations and geological model	92
8		PMI	
0	81	Geology of the area	
	8.2	Subdivision and chemistry	100
	83	Mineralogy	100
	8.4	Nickel-copper ore	111
	8.5	Genetic considerations	111

CONTENTS

	8.6 Geological model	114
9	SUBECONOMIC INTRUSIONS	115
	9.1 Ekojoki	115
	9.1.1 Geology, petrochemistry and mineralogy	116
	9.1.2 Nickel-copper mineralisation	121
	9.1.3 Petrogenetic considerations	123
	9.1.4 Geological model	126
	9.2 Rausenkulma	126
	9.2.1 Observations	126
	9.2.2 Genetic considerations and geological model	132
	9.3 Rörmyrberget	133
	9.3.1 Observations.	133
	9.3.2 Genetic considerations	139
10	BARREN INTRUSIONS	141
	10.1 Posionlahti	141
	10.1.1 Observations	142
	10.1.2 Genetic considerations	144
	10.2 Porrasniemi	145
	10.2.1 Subdivision, chemistry and mineralogy	145
	10.2.2 Radiometric dating	149
	10.2.3 Geological model	150
	10.3 Alter do Chão	151
	10.3.1 Subdivision mineralogy and chemistry	152
	10.3.2 Petrogenetic considerations and geological model	154
11	Co#-Ni# SYSTEMATICS IN STUDIED MAFIC-ULTRAMAFIC INTRUSIONS	157
	11.1 Examination of Co# as a tool of sulphide segregation	157
	11.1.1 Reliability of assays	157
	11.1.2 Resetting of Co# and Ni# in subsolidus stages	161
	11.2 Sulphide segregation	164
	11.2.1 Initial Co#-Ni# and sulphide segregation trends in the case study intrusions	164
	11.2.2 Quantitative models	165
	11.3 Discussion	170
PA	NRT III: PRACTICE	173
12	FERTILITY ANALYSIS	173
	12.1 Parameter 1: Primitive character of the magma	174
	12.2 Parameter 2: Extent of sulphide saturation	175
	12.2.1 Contamination as an indicator	175
	12.2.2 Sulphides as an indicator	178
	12.3 Parameters 3: Ni-rich, chalcophile-undepleted magma	179
	12.4 Parameter 4: Sulphides are magmatic and equilibrated with a large amount of magma	180
	12.5 Parameter 5: Coeval primitiveness	182
	12.6 Parameter 6: Sulphide accumulation	185
	12.7 Parameter 7: Fractionation or mobilisation of sulphides	186
	12.8 Auxiliary parameters	187
	12.9 Ranking of the case study targets according to their ore hosting potential	189
13	LOCALISING THE ORE AND ESTIMATING ITS GRADE AND SIZE	193
	13.1 Methods for localising the Ni-Cu ore	193
	13.2 Estimating the grade and tonnages	196
14	TESTING THE PRACTICABILITY OF THE OD INDEX	197
	14.1 Effect of number of samples and analysis methods	197
	14.2 Specific tests on the Råna intrusion.	201
	14.3 Svecofennian intrusions of Finland	203
	14.4 Thompson nickel belt	207
	14.5 Cape Smith belt	209
	14.6 World-class Ni-Cu deposits	210
	A	

14.	6.1 Conclusions of the test with world-class deposits	
15 AP	PLICATIONS IN PGE EXPLORATION	
15.1	Relationship between PGE and Co#	
15.2	Testing of Co# as a PGE exploration tool	
15.3	Additional information obtained from Ni#	223
15.4	Discussion	
15.5	Discrimination of PGE potential intrusions	227
16 DIS	SCUSSION	
16.1	Are the sample sets biased?	
16.2	Comparison to earlier studies	
16.3	Open nature of the magmatic systems and consequences for exploration	
16.4	Spatial variation in the nature of Svecofennian mafic – ultramafic intrusions	
17 SU	MMARY AND CONCLUSIONS	
18 AC	KNOWLEDGEMENTS	
19 RE	FERENCES	
20 TE	RMS AND NOMENCLATURE	
21 INI	DEX	
22 AP	PENDIX: DATA CD	

The seeds of this work were planted in 1983, when I started my fieldwork for an M.Sc. Thesis in the Porrasniemi intrusion in Southern Finland. Encouraged by Professor Tauno Piirainen and geologist Jarmo Vesanto, I applied cumulus terminology and systematics comprehensively probably for the first time in the studies of Svecofennian intrusions, and recognized that a similar approach would bring results in the studies of other Svecofennian intrusions, too. As a postgraduate, I continued together with Petri Peltonen to study intrusions in the Vammala area and then also applied chemical composition of chrome spinel, nickel content of mafic silicates and isotopic signatures in the ore potential evaluation of the intrusions.

Between 1990 and 2000 I had the opportunity to participate in several nickel exploration projects of the Outokumpu Group. My task as a petrochemist and mineralogist was to give petrological support for the field geologists working in Finland, Sweden (Åkerman 2003), Norway, Canada, Portugal, Spain and Australia. Among many other problems, the most important question was always: *Does this intrusion or extrusion host nickel ore, and if it does, where it is located?* And: *Which of the targets in the area are the most prospective?*

This study is a descendant of Outokumpu's Nickel Programme and GeoNickel project. The Nickel Programme was established in 1960 in order to collect a database on Finnish maficultramafic rocks for the use of Ni exploration (Häkli 1971), and currently its descendant, the NIXPLOR database, includes petrological, mineralogical and geochemical data of more than 50 000 hard rock samples. The geological branch project of the GeoNickel (Integrated Technologies for Minerals Exploration, Pilot Project for Nickel Ore Deposits 'GeoNickel', Aarnisalo et al. 1999) aimed to develop geological, lithogeochemical, mineralogical and petrological models and tools in order to discriminate nickel sulphide-potential intrusions and extrusions from barren ones and to locate Ni sulphide deposits within them or their surroundings, by applying computer simulated exploration models (Aarnisalo et al. 1999, GeoNickel 1999). This work was done in cooperation with Outokumpu, BRGM (Le Bureau de Reserches géologigues et minères, France) and Turku University. The main researchers of the project were T. Augé of BRGM; I. Ylander, J. Liipo and P. Lamberg of Outokumpu; and Professor H. Papunen with T. Halkoaho, J. Välimaa and J. Liimatainen of Turku University.

This compilation continues from where the GeoNickel left off. GeoNickel aimed at practical solutions. and the approach was auite straightforward. This study will discuss more widely the background and theories behind the applications and will test the tools in two cases: Nickel Programme data on Svecofennian intrusions and world class nickel deposits. I am personally responsible of the text and work presented here although the preliminary results were born in co-operation with large number of researchers. I have had the privilege to work with several scientists, experts and professionals in the course of this work. The original unpublished reports are referred to in this thesis with my acknowledgements to the people concerned.

Now that Outokumpu has finished nickel exploration, it seems that there is a lot of knowledge, experience and data in danger of vanishing and remaining unexploited. Publications from Outokumpu geologists about nickel exploration since the Geological Survey of Finland Bulletin 333 (1985) have been very few, the GeoNickel paper (Aarnisalo et al. 1999) being the most important. Therefore, besides the other results of the research this work attempts to document the philosophy and methods used in the nickel sulphide exploration in Outokumpu.

PART I: GENETIC CONCEPTS

1 INTRODUCTION

Sulphidic deposits of nickel-copper-platinumgroup elements (PGE) are almost solely of magmatic origin, and the stages of their formation are 1) partial melting of the mantle, 2) transfer of the magma to the crust, 3) formation of the phase that collects the metals, 4) concentration of that phase (Figure 1, Naldrett 1989, 2004 and Barnes and Maier 1999). In the case of nickel-copper deposits, the metal collector is the sulphide phase and the processes are sulphide segregation and concentration. Ni-Cu-PGE deposits can be subdivided into sulphide- and PGE-dominant deposits (Naldrett 2004, Barnes and Maier 1999). In the former ore types, the sulphide content is normally above 10% and in latter less than one percent. This study deals with sulphide dominant Ni-Cu(-PGE) deposits, their geology, formation and lithogeochemical exploration techniques.

The formation of Ni-Cu sulphide deposit requires 1) hot, primitive, high-magnesium magma, 2) a mechanism to achieve sulphur saturation and immiscibility of sulphide melt, 3) mechanism enhance reaction between to sulphides and sufficient amount of magma to concentrate chalcophile elements to an economic level, and 4) magma dynamics and physical traps to concentrate magmatic sulphides in a restricted locality where their abundance is sufficient to constitute an ore (Fig. 1, Naldrett 1999, Lightfoot and Keays 1994). The most magmatic Ni-Cu-(PGE) sulphide deposits are interpreted as having been formed from the magmas that were originally sulphide-undersaturated (Keavs 1982, 1995, Naldrett and Barnes 1986, Lesher and Burnham 2001). Crustal contamination has been proven to be the key process in the formation of the ores in almost all the studied Ni deposits (see reviews by Naldrett 1999 and Lesher and Burnham 2001). Contamination causes sulphide segregation either directly by incorporation of crustal sulphur and increasing the sulphur content of magma or indirectly by decreasing the sulphur solubility by changing the magma composition.



Figure 1 Stages and requirements (*in italics*) of nickel sulphide ore formation, modified after Naldrett (1966, 1989, 2004), Naldrett and Cabri (1976), and Barnes and Maier (1999).

A wide range of tools is used in nickel sulphide exploration. After the selection of the exploration area or district, ultramafic and mafic and extrusions are located by intrusions geological mapping, geophysical surveys, satellite image processing, overburden geochemistry and erratic boulder tracing. This work has been done in most of the potential nickel exploration areas of the world. Potential targets are further evaluated by analysing and assessing available data. After the exploration rights of potential targets have been obtained, more data will be acquired by geological, geophysical, remote sensing, and overburden geochemical means. This aims at locating potential sites, which are then further tested by drilling in a belief and hope of discovering sulphide nickel-copper ore.

Geophysical and overburden geochemical methods aim at the direct identification of sulphide enrichment, but geological tools should give an answer to more difficult questions: is the rock sequence favourable for the occurrence of Ni-Cu ore, and if the answer is positive, in which part of the geological formation is the sulphide ore located?

Modern petrological studies of sulphide nickel

ores and their exploration techniques are directed to complicated, commonly timeconsuming and expensive methods like Re-Os isotopes (Hulbert and Grégoire 1993; Lambert et al. 1998, 1999, 2000; Sproule et al. 1999; Brooks et al. 1999), sulphur isotopes (Ripley 1999, Ripley et al. 1999), oxygen isotopes (Ripley 1999, Ripley et al. 1999, 2000), ratios of some trace elements (Lesher and Burnham 2001, Barnes et al. 1993), and trace element contents of accessory minerals (Barnes 1998, 1999a, 2000; Barnes and Brand 1999). Most of the techniques described above have been validated in known ore deposits and ore samples, but they are not, however, adequately applied in grass-roots nickel exploration. The main reason is not the cost of the analyses, but in the difficulty in interpreting the results.

Apart from the trials by Häkli (1971), Barnes et al. (2004) and Lesher et al. (1999, 2001) the major element geochemistry and basic mineralogy are poorly applied in nickel exploration, because a common understanding and widely accepted criterion for discriminating nickel sulphide-bearing intrusions is still an open question.

2 AIM AND CONTENT OF THE STUDY

The main objective of this study is to find new practical tools, approaches and solutions to the question: how can petrochemistry and mineralogy be applied to discriminate barren and mineralised intrusions in Ni sulphide exploration? Another issue is whether it is feasible to make expensive isotope analyses and apply other sophisticated methods, or can just simple inexpensive and fast whole-rock geochemistry give equally valuable answers? Moreover, what is the adequate sampling density? Is there a reason to sample every possible place (outcrops, drill holes, trenches) at a five-meter interval or can we get the same information just by a small number (10-30) of samples of the target? The main objective is to find methods, which could be applied routinely without deep-level scientific research in each case. The methods should be unambiguous, straightforward, and it should be possible to construct a flow sheet for semi-automated data processing.

As there is a risk that the main aims of the study cannot be realised, a number of other goals, which are easier to attain and can give fruitful results, were set. In terms of petrology this study has both methodological and empirical aims. Several concerning geochemical factors characteristics of host intrusions will be introduced and calculated in the methodological chapters in part I. Since the igneous intrusive bodies treated here are commonly metamorphosed and have mineral compositions

different from the primary igneous assemblages, normative mineral compositions from the wholerock analyses will be calculated in order to apply adequate cumulus terminology to the structural interpretation of an intrusion.

The empirical part II consists of petrological studies of nine intrusions, of which three are fertile, i.e. mined as Ni-Cu ores, three are subeconomic Ni-Cu deposits, i.e. deposits with uneconomic mineralisation, and three are barren intrusions. This second part applies the methods introduced in the first part. The main attention is paid to the identification of diagnostic features related to Ni-Cu ores and their host intrusions. Potential nickel exploration tools are preliminary discussed at the end of the description of each target. The tools are further discussed, evaluated and tested in part III, Practice. Finally an answer will be given to the questions: *Is it possible to estimate from a randomly selected and limited amount of lithogeochemical data, whether the intrusion hosts an enrichment of nickel sulphides, and what sort of mineralisation it is in terms of grade and tonnages, and where it is located?*

3 GENETIC CONCEPTS

The factors controlling the nickel sulphide ore formation processes in the basic magmatic system are: 1) the primitive character of the magma, 2) nature and magnitude of the sulphide saturation mechanism and process, 3) volume of the magma equilibrated with sulphides, 4) efficiency of sulphide segregation and accumulation (Figure 1). Lithogeochemical and mineralogical tools applied in nickel exploration focus on the evaluation of these four processes and factors (Table 1). The ore forming process and the way they are measured and applied in nickel sulphide exploration are reviewed in the following on the basis of a literature survey. The review is not complete, but it will introduce different methods to be tested in the case studies. For more comprehensive reviews, the reader is referred to papers of Naldrett (1989, 1999, 2004), Lesher and Burnham (2001). Only the new indices introduced in this study – the nickel and cobalt numbers – will be discussed in more detail (chapter 3.5).

Table 1. Summary of the lithogeochemical and mineralogical tools applied or proposed to be used in nickel sulphide exploration. References are given in the text.

		Lithogeochemical tools applied in 1	Ni exploration
Factor	Feature to monitor	Intrusions	Komatiites
Primitive magma	Mg, Ni-rich magma Not PGE-depleted.	-Mg# of olivine, Opx, Cpx -Pd/Cu vs. Pd plot -Magma type (boninite)	-Ni vs. Cr plot -Ni, Cr vs. MgO plot -Incompatible vs. MgO -Mg-Fe relationship
Sulphide saturation	Contamination: Anomalous contents of incompatible elements	-HFSE -Zn content of chromite -Cu/Zr ratio	-REE -Isotopes of Re-Os -Ni-Mg relationship
Sulphide segregation	Chalcophile element, especially PGE, depletion	-Ni vs. Mg# of Ol, Opx, Cpx -Pd/Cu ratio -Tl, Eu	-Ni vs. MgO of olivine cumulates
Sulphide accumulation	Favourable site for accumulation: feeder zone, bottom parts, depression structures, channelised flows	-MgO -Presence of olivine ad- and mesocumulates -Mg# of olivine, Opx, Cpx	-MgO -Presence of olivine ad- and mesocumulates -Incompatible vs. MgO -Ni vs. Cr plot

This study focuses on specific exploration important point in mineral exploration is the tools, but one should not forget that the most correct geological model of the exploration

province, area and target. The model tells the potential sites of exploration, and it is being continuously tested and revised while more information is gathered. In modelling, all possible geological, geochemical and geophysical tools are applied. Normal lithogeochemical work is often essential by giving solid and unambiguous information. Details of the geological modelling will be discussed in the following only in the cases they are appropriate for the development of the present tools

3.1 Primitive character of magma

Primary magma is a magma which has a chemical composition that has not changed since its formation in the mantle. It is a liquid composition from which other associated and cogenetic magmas can be derived by processes of crystal fractionation and accumulation. contamination, liquid immiscibility and magma mixing (Basaltic Volcanism Project 1981). Primitive magma is commonly in equilibrium with olivine, and has high Mg# (68-75, 100*Mg/(Mg+Fe) in cation proportions), and concentrations of Cr, Ni and Ni/Cu are high. The composition of primitive magma depends on the amount of partial melting and character of the source area, primitive melt derived from pristine mantle peridotite is different from that derived from a metasomatised or depleted mantle.

Parental magma, in comparison, is magma from which a certain intrusion has crystallised. For practical reasons the term primitiveness is here applied to indicate a primitive character of the magma. The primitiveness of the parental magma of a cumulate body can be evaluated from the chemical compositions of the earliest cumulate minerals, of which olivine is most utilized. The primitiveness is directly proportional to the *forsterite* content of olivine and magnesium number. Mg#=100*Mg/(Mg+Fe) (in cation proportions), of mafic silicates. The Mg# of cumulate phases may decrease by some percentage in the subsolidus re-equilibration with the trapped liquid (Barnes 1986). Olivine composition of a single cumulate sample can be calculated from normative compositions as explained in chapter 4.5.4. It can also be estimated from a set of olivine cumulate analyses

if the olivine is the only cumulus mineral by extrapolation in an MgO *vs.* incompatible element x-y diagram to a zero incompatible element content (Barnes et al. 1988, Chai and Naldrett 1992a). A simple MgO content of the cumulate has also been used (Naldrett and Arndt 1976).

A primitive sulphide unsaturated olivine normative magma is liable to produce nickel sulphide ores. This is caused by the following factors (modified after Naldrett 1999, Lesher and Stone 1996). 1) Primitive magmas formed in the partial melting of the mantle are rich in base metals. 2) The nickel content of the magma is directly proportional to the concentration of normative olivine and MgO (Figure 2). 3) A primitive olivine normative magma is hot, hence capable of dissolving and assimilating country rock. 4) The more primitive the magma, the lower the viscosity and consequently the better are possibilities for efficient segregation and enrichment of sulphides in case sulphide oversaturation occurs. In magma-olivine system the nickel enters readily in the lattice of olivine, and therefore it is essential for the generation of a Ni-rich sulphide melt to form early and before a significant crystallization and segregation of the olivine. Primitive mafic magma is also rich in base metals, which requires that neither the sulphides nor olivine have segregated significantly prior to the emplacement and formation of the intrusion in question. This is why the ultramafic rocks and the earliest cumulates are the most favourable for nickel-rich sulphides.

In spite of the evident potential of the primitive magmas to generate Ni-Cu deposits,

primitiveness is not a key factor in nickel sulphide formation, because the parental magma of host intrusions and extrusions of sulphide ores vary from komatiitic (e.g. Mt. Keith) to basaltic (e.g. Voisey's Bay). In terms of MgO content, the range is from less than 10 wt.% to 30 wt.%. Magma primitiveness, however, gives an estimate on the composition of the sulphide fraction (sulphides recalculated to 100%) of a possible ore. Nickel tenor, i.e. nickel content of the coexisting sulphide fraction, decreases and the copper content increases while the primitiveness of the magma decreases (e.g. Naldrett 2004).

Magma primitiveness has been applied in nickel exploration as background information in province and area selection. If komatiites are present in the province, then geological models and practices of exploration are different than in the area of basaltic intrusions. In exploration of intrusive environments, the Mg# of mafic silicates (olivine, orthopyroxene, clinopyroxene, and in some cases also amphibole) has been used mainly in localisation of the most primitive cumulates of the intrusion, since they are the most prospective ones (chapter 3.4). To give some examples, Grundström (1980, 1985) localised the olivine cumulates and adjacent Ni-Cu ore at the Laukunkangas intrusion by tracing the Mg# of orthopyroxene. Thompson and Naldrett (1984) used a Mg# of orthopyroxene and olivine to locate the most favourable site of exploration in Katahdin and Moxie plutons in northern Appalachians.

In komatiites the volcanic facies involving channelised flow has a strong association with mineralisation. These more prospective volcanic facies can be identified by their lower Cr contents and Cr/Ni ratios from sheet flow and ponded lava lake sequences with low potential for hosting Ni sulphide deposits (Barnes and Brand 1999).



	Туре
•	ARC tholeiite
\triangle	Basalt
X	Basanite
0	Boninite
+	Ferropicrite
	Flood basalt
∇	High MgO basalt
*	Komatiite
\diamond	Komatiitic basalt
I	MORB
—	Mantle
•	Melilite
▲	Nephelinite
•	OIT
<u> </u>	Olivine basalt
	Olivine melilite
0	Olivine nephelinite
0	Olivine tholeiite
	Picrite
<u>•</u>	Picritic basalt
	Tholeilte

Figure 2. Nickel content of the parental magmas vs. MgO content. Data sources: Alapieti and Lahtinen (1989), Arndt et al. (1977), Barnes et al. (1995). Basaltic Volcanism Project (1981), Bloomer and Hawkins (1987),Clague and Dalrymple (1988), Francis (1990), Francis and Ludden (1990). Frey et al. (1978), Glotov et al. (2001), Hanski (1992), Irving (1980), Jahn et al. (1982), Klewin and Berg (1991), Lahaye et al. (2001), Maaloe and Aoki (1977).McDonough and Frey (1989), McIver et al. (1982), Morten (1987), Pedersen (1979), Peltonen (1990), Rajamani et al. Schaefer (1985),and Morton (1991), Sobolev and Slutskii (1984),Wilkinson Binns and (1977) and Whilshire et al. (1988).

In PGE exploration, identification of a specific PGE-rich magma type for high potential for ore formation has been regarded as essential. In the Tornio-Näränkävaara layered intrusion belt, the mineralised megacyclic units were identified on the basis of chromium content, which is high in megacyclic units crystallised from the boninitic magma (Alapieti and Lahtinen 1989, Alapieti et al 1990, Halkoaho 1994). The Svecofennian intrusions dominated by peridotites and norites have been regarded as having more potential for Ni-Cu deposits than the pyroxenitic intrusions (Mäkinen 1987).

3.2 Sulphide saturation

Primitive and nickel-rich magma should meet sulphide saturation in the course to the formation of Ni-Cu sulphide deposit. Sulphide saturation is reached when the sulphur content of the magma exceeds the magma capacity to dissolve the sulphur. Sulphide saturation can occur in magmatic systems if: 1) the temperature decreases, 2) the pressure increases, 3) the oxygen fugacity increases, 4) the sulphur fugacity decreases, 5) the sulphur content increases, 6) composition changes in a way that sulphur content in the sulphide saturation decreases (Buchanan and Nolan 1979, Buchanan et al. 1983, Haughton et al. 1974, Shima and Naldrett 1975, MacLean 1969, Wendlandt 1982, Huang and Williams 1980). The addition of silica and aluminium will normally have the effect of driving the system towards the sulphide saturation while an increase in iron, magnesium, calcium and titanium contents will have the opposite effect (Fincham and Richardson 1954). Mavrogenes and O'Neill (1999) concluded that unless a mafic melt has either undergone extensive low-pressure fractionation, or has been able to assimilate sulphur, it could not arrive at the surface sulphide-saturated. Also oxidationreduction reactions cannot cause sulphide saturation. During adiabatic cooling the sulphide saturation cannot be reached, because the influence of temperature on SCSS (sulphur content of the silicate melt in sulphide saturation) along a melt adiabat is overwhelmed by the effect of decreasing pressure. This is also true for magmas intruded in the upper crust; therefore significant and suitable crustal contamination is required for the sulphide saturation.

Since cumulus olivine incorporates considerable amounts of nickel from the melt, the sulphide saturation and sulphide melt immiscibility should occur early in the formation of the cumulate body. An important question for the sulphide nickel exploration is, how closely in time and space are the two essential processes related: sulphur saturation / sulphide melt immiscibility and sulphide segregation accumulation from a large volume of magma. There are two opinions on the timing of the sulphide saturation and segregation. (1) In PGE deposits and in komatiitic Ni deposits, the sulphide segregation and deposition follows immediately or very soon after the sulphide saturation and precedes the accumulation of silicate cumulus crystals. In PGE deposits the immiscible sulphide droplets must be exposed to a large volume of molten silicate magma in order to sweep the trace amounts of PGE from silicate to sulphide melt. In the Mt Keith type of komatiitic deposits, the sulphide droplets will settle down immediately together with olivine due to the low viscosity of magma (Lesher et al. 1999, Keays 1982 and Naldrett and Barnes 1986). (2) According to the transportation model, the sulphide droplets are carried with the flowing magma and deposited far away from the saturation site when the magma flow slows down. This model is supported by the presence of sulphide globules in the Noril'sk and Sudbury deposits, and by recent experimental studies, which have shown that flowing magma can carry dispersed sulphide droplets considerable distances (Bremond et al. 1999, 2001). In addition, the sulphide droplets included in a cumulus chromite in the Stormi Ni-Cu ore proves according to Peltonen (1995d) that immiscible sulphide liquid is formed in the magma at an early stage, significantly earlier than the sulphides accumulated at the base of the intrusion.

3.2.1 Crustal contamination

The case studies of nickel sulphide ores have shown that in the vast majority of the cases the most important agent in sulphide saturation has crustal contamination. Examples been are numerous: Pechenga (Barnes et al. 2001, Hanski 1992), Alexo, Texmont and Hart in the Abitibi greenstone belt of Ontario (Lahaye at al. 2001), Noril'sk, Ranklin Inlet (Hulbert and Grégoire 1993), Voisey's Bay (Lambert et al. 1999, Li et al. 2000, Li and Naldrett 2000, Amelin et al. 2000, Ripley et al. 2000, Lambert et al. 2000). Actually there are very few cases where contamination is not regarded as a major process leading to Ni sulphide ore formation, and some of them at least because of lack of such studies (e.g. Jinchuan, Naldrett 1999). The assimilation of sulphur-bearing country rock seems to be the mechanism to achieve sulphide saturation in magma.

Since the crustal contamination plays a major role in the sulphide saturation, most of the studies on geochemical Ni-Cu-(PGE) sulphide exploration methods have been concentrated in identifying the contamination process from the barren cumulates close to the ore. In guite many Ni-Cu-(PGE) deposits there is both physical and geochemical evidence on crustal contamination, as listed by Lesher and Burnham (2001, Table 1), but in numerous deposits the evidence is missing or it can be found only in the ore or only locally outside the ore. Significant crustal assimilation has been quite frequently found also in layered cumulate bodies, which are barren of Ni-Cu Kaelvegletscher sulphides (e.g. ultramafic complex in Greenland, Praegel and Holm 2001).

The intruding hot magma is in thermochemical imbalance with its host rock, and the surroundings will become heated and the magma can interact with the country rocks. The reactions range from total melting of the host rock and mixing of the melts to partial assimilation of wall rock components, especially volatiles (e.g. as explained at Duluth, Ripley 1986). Crustal contamination causes the magma to reach sulphide saturation in many ways, since - even if sulphur species do not exist as a contaminant the temperature tends to decrease and the concentrations of silica and aluminium increase in the process.

The contaminants promoting the sulphide saturation are sulphur-bearing sediments, the composition varving anhydrite-bearing evaporates (Noril'sk), to sulphide-bearing pelites (e.g. Kambalda, Cape Smith. Muskox) and black schists. Graphite-bearing mica gneiss or black schist is a relatively common contaminant, since its presence has been documented in at least the following Ni-Cu deposits: Duluth (Mainwaring and Naldrett 1977); Pechenga; Alexo, Texmont and Hart of Abitibi greenstone belt; Voisey's Bay (Naldrett et al. 2000). Graphite is also closely associated with PGE in Merensky Reef and Platreef deposits in the Bushveld Complexes (Buchanan and Rouse 1984). In Stillwater, graphite is encountered in ultramafic pegmatoids below the J-M reef (Volborth and Housley 1984). In Svecofennian mineralised mafic intrusions, graphite is often associated with sulphides, as in Kotalahti (Papunen 1971), Kylmäkoski (Papunen 1985; Gervilla et al. 1997 and 1998), Hitura (Papunen 1971) and Herttuala (Peltonen 1992). Graphite is also related with sulphides in the following intrusion hosted Ni-Cu mineralisations: St. Stephen, Goodwin Lake, Mechanic and Portage Brook in New Brunswick (Paktune 1987, 1988a, b, c and 1989), Moxie, Katahdin, Union and Warren in Maine (Rainville and Park 1976), Huntly and Insch in Scotland (Fletcher and Rice 1998, Fletcher et al. 1989, Fletcher 1988) and Keivitsa in Finnish Lapland (Mutanen 1989, 1996 and 1997).

Black schists are common wall rocks of the intrusions studied here, too. They are metasedimentary rocks composed of graphite, pyrrhotite, minor chalcopyrite and sphalerite, quartz and micas. They are normally low in base metals, but compared to magmatic Ni-Cu sulphides they are rich in zinc and molybdenum. Vanadium content is also high compared to pelitic rocks (Loukkola-Ruskeeniemi 1999).

Graphite can crystallise from magmas in layered intrusions as shown by Elliot et al. (1981), Ulmer (1983), Ballhaus (1988) and Kornprobst et al. (1987). However. the sedimentary origin of graphite has been suggested on the basis of field relationships and by the carbon isotope composition (Liebenberg 1970, Buchanan and Rouse 1984, Toysinthiphoexay et al. 1984, Fletcher 1988). In contamination of the basaltic magma by black schist, the elements may be distributed between five phases: 1) silicate liquid, 2) crystallizing minerals, 3) immiscible sulphide melt, 4) volatile phase and 5) restite. Gaseous or solid carbonaceous contaminants will be dissolved in magma as carbon, or degassed, until an equilibrium between C, CO and CO₂ is attained (Mathez and Delaney 1981). This depends on the magma composition and, above all, on total pressure. At a pressure of only 400 bar (ca 1.5 km depth), the graphite is stable in basaltic magmas up to 1200° C without metallic iron, i.e. at oxygen pressures above the IW buffer line (Goodrich and Bird 1985). Sulphur in the black schist may be dissolved in silicate liquid, but after the sulphide saturation, will form an immiscible sulphide liquid, which is in equilibrium with the silicate liquid. Non-volatile elements will distribute between existing phases.

The mantle-derived parental melt composition depends on the degree of melting. The generation of magma by a large degree of melting of the mantle produces a melt rich in compatible elements and poor in incompatible elements. If that kind of magma interacts with crustal rocks, magma composition may change and become contaminated by crustal components. Elements with great differences in concentrations between mafic-ultramafic magmas and continental crust are suitable to trace the contamination process. LILE (large ion lithophile elements), LREE (light rare earth elements) and HFSE (high field strength elements) have been applied (e.g. Lesher and Burnham 2001). Also, the Se/S ratio can indicate crustal contamination (Eckstrand et al. 1989, Lesher et al. 1999).

The sensitive elements and isotopes to indicate crustal contamination of Ni-Cu sulphide deposits vary from area to area. According to Lesher and Burnham (2001) the sensitivity order of isotopes is S~Pb>Nd>Os at Kambalda, S>Os at Raglan, S>Sr>Os at Noril'sk Os>>Nd~Pb~S at Pechenga and C>S>Nd>Pb~Os at Duluth.

Indications of contamination have been applied to screen the potential provinces and areas of Ni sulphide exploration. Since external sulphur is required, one of the key factors in assessing the area has been the existence of sulphur-bearing country rocks (Naldrett 1999, Lesher and Stone 1996). REE patterns (Barnes et al. 1995), S/Se ratios (e.g. Eckstrand et al. 1989), and crystallization paths (Perring et al. 1992, Makkonen 1996) have been applied to indicate contamination of the exploration target.

Groves et al. (1977 and 1983) proposed the Zn content of chromite as an indication of contamination of komatiites by sedimentary materials and therefore as a tool in Ni sulphide exploration. This was, however, questioned by Barnes (1999a). Lamberg and Peltonen (1991) and Peltonen et al. (1992) discovered that the chromite of the Vammala intrusion, which hosts Ni-Cu sulphide ore, is rich in zinc compared to barren intrusions. Peltonen et al. (1992) carried out a pilot test of tracing the zinc-rich chromite in glacial tills in the Vammala area, but the result was not very encouraging. Chromite is a resistant mineral to weathering and it has been proposed to monitor its unique chemistry in nickel exploration in two areas. Barnes (1998, 1999a, 199b and 2000) concluded that the potential of chromite as a pathfinder in the case of komatiite-hosted Ni deposits is limited due to change in chromite chemistry in metamorphic reactions.

3.2.2 Identification of sulphide-saturated magmas

The identification of sulphide-saturated magmas is an important question in this study and in nickel sulphide exploration in general. If the magma can be sampled, as in the case of volcanic rocks, identification can be done by the presence of immiscible sulphide droplets (e.g. Mathez 1976) or by analysing the sulphur concentration of the melt. In cumulate rocks the question is more complicated. In order to get some boundary values of sulphur-saturated rocks, a simplified case is considered, where an orthocumulate rock crystallised from sulphur-undersaturated magma consists of 50% cumulus phases and 50% trapped liquid. The system has been closed in a postcumulus stage. If the maximum sulphur content of the liquid in sulphide saturation is 1400 ppm (Mavrogenes and O'Neill 1999, Poulson and Ohmoto 1990), then 50% trapped liquid with less than 1400 ppm sulphur would produce less than 0.18% sulphides in the crystallised cumulate, as

Table 2. shown Therefore cumulates in containing more than 0.2% sulphides must have crystallised from sulphide-saturated magma. To be on the safe side, a value of 0.3% sulphides is used here as the border value. If the normative sulphide content of a cumulate is above 0.3%, the sample is regarded to contain cumulus sulphides and formed from the sulphide-saturated magma. In this study for such cumulate samples the phrases sulphide cumulate (e.g. olivine-sulphide cumulate) or with cumulus sulphides or with sulphides as cumulus phase are used.

Naldrett (2005) rejected this direct method on the basis of tests on a series of spinifex-textured lavas from the Abitibi greenstone belt since he found that sulphides had been extremely mobile during metamorphism (cf. Duke and Naldrett 1976). Naldrett (2005) suggested that the best approach to identify the sulphide saturation was to monitor the depletion features caused by sulphide segregation, as discussed in the following chapter.

Table 2. Evaluation of the sulphide content of a cumulate rock crystallized from sulphur undersaturated magma.

Maximum sulphur content in trapped liquid	1400	ppm
Maximum sulphur content in an orthocumulate which has crystallised from sulphide undersaturated magma and where sulphide melt is not a cumulus phase	700	ppm
Sulphur content of sulphide phase	38	wt.%
Maximum sulphide content of an		
orthocumulate, where sulphide has crystallised from sulphur undersaturated trapped liquid	0.18	wt.%

3.3 Sulphide segregation

Sulphide saturation of a primitive magma as such is not enough to produce an ore deposit. The appropriate physical environment is required to bring the sulphide melt into equilibrium with a considerable volume of magma so that the sulphide liquid becomes adequately enriched in chalcophile elements. Nickel, copper, cobalt, the platinum-group elements (Pt, Pd, Rh, Ru, Ir and Os), and gold partition between the co-existing sulphide and silicate melts strongly into sulphides relative to silicate magma and silicate minerals. In a simple case, the partitioning of an element between different phases can be described by the Nernst partition coefficient D, i.e. distribution coefficient, as follows:

$$D_i^{a/b} = \frac{C_i^a}{C_i^b}$$
 (Equation 1),

where C refers to concentrations of element i in phases a and b. A partition coefficient can be based either on weight percentages or mole fractions. The latter case is mainly used in modelling. Sulphide melt / silicate melt partition coefficients for chalcophile elements in basic-

ultrabasic systems are in the order 30 for cobalt, 100-1000 for nickel, 600-1400 for copper, and 10^3-10^5 for platinum-group elements and gold (Table 3 and reviews in Lesher and Stone 1996 and Barnes and Maier 1999). It is often more useful to model the composition of the sulphide melt in terms of the initial composition of the silicate magma. In cases where the mass ratio of silicate magma to sulphide melt is very large, equation 1 gives a satisfactory answer, but when this ratio decreases a more general expression of Campbell and Naldrett (1979a) has to be used:

$$Y_i = \frac{D_i \times X_{0i} \times (R+1)}{(R+D_i)}$$
 (Equation 2),

where Y_i is the concentration (wt.%) of an element i in the sulphide liquid, X_{0i} is the initial concentration of the element in the silicate melt, and D_i is the sulphide/silicate melt partition coefficient for the element *i* and R is the ratio of the mass of silicate magma to the mass of sulphide melt.

If sulphur derives from an external source, then equation is as follows (Naldrett 1981):

$$Y_{i} = \frac{D_{i} \times X_{0i} \times R}{(R+D_{i})}$$
 (Equation 3).

If the assimilant is metal-bearing, then the expression is (Lesher and Burnham 1999):

$$Y_{i} = \frac{D_{i} \times (X_{0i} \times R + Y_{0i})}{(R + D_{i})}$$
 (Equation 4),

where Y_{0i} is the initial concentration of element *i* in the initial sulphide phase.

In fractional segregation of sulphides the Rayleigh equation is used:

$$Y_i = D_i \times X_{0i} \times F^{D_i - 1}$$
 (Equation 5),

where F is the fraction of original liquid that remains.

If sulphides continuously react with fresh magma, the process is analogous to zone refining and the equation for distribution is (Cox et al. 1979, Naldrett 2004):

$$Y_i = X_i \times \left[D_i - \left(\{ D_i - 1 \}^* e^{-\left(\mathcal{Y}_{D_i} \right)^* N} \right) \right] \quad (Equation \ 6),$$

where N is the ratio of the amount of magma passing through the system and reacting with the sulphide, to the amount of sulphide in the system.

According to equations 2-6, the concentrations of base and noble metals in sulphides is initially controlled by the Nernst partition coefficient of element between the sulphide and silicate liquids, the mass ratios of equilibrated sulphide and silicate liquids, the initial content of an element in a silicate liquid, and if sulphur derives from an external source then also the content of element in incorporated sulphide liquid.

Three end members can be distinguished in the way sulphides react with and segregate from a magma (Naldrett 1989, 2004): 1) In batch segregation, a significant proportion of sulphide becomes immiscible and equilibrates with the silicate magma in a single stage. This process may occur in a small portion of magma, and then it is called a localized batch equilibration. 2) In zone refining, sulphides are introduced at the top of a magma chamber and slowly settle through it, or alternatively. sulphides are located in a hydrodynamic trap within a magma conduit along which fresh magma continues to flow and interact with sulphides (Brugmann et al. 1993, Naldrett et al. 1995, 1996). 3) In fractional segregation, a very small amount of sulphide becomes continuously immiscible, equilibrates with the silicate magma, and is removed by settling or in some other way to communicate with magma. Fractional segregation of sulphides is commonly associated with fractional crystallization and segregation of olivine.

Segregation of sulphides leaves behind a residual magma, which is depleted of elements, preferentially partitioning in sulphides (Table 3). This will be called in this study chalcophile element depletion. For economically important metals the depletion order is: Co<Ni<Cu<<PGE. The degree of the depletion is proportional to the partition coefficient between the sulphide and silicate liquids and to the total amount of segregated sulphides, i.e. the R factor in batch segregation as shown in Figure 3. If the same amounts of sulphides fractionate with the three

processes described above, the magnitude of the chalcophile depletion is highest in fractional segregation and lowest in batch segregation. Figure 3 demonstrates clearly that the removal of even a small amount of sulphides will cause a dramatic depletion in palladium as well as in other PGEs, while the drop in nickel, cobalt and copper is insignificant. Consequently, the formation of PGE ores requires magma, from which sulphides have not been segregated previously, while the term is not so harsh for Ni-Cu ores.

The chalcophile element depletion has been frequently applied in nickel sulphide exploration. The depletion is analysed mainly from the nickel content of olivine, because olivine is commonly the first mineral to crystallise from the magma's potential to produce Ni-Cu-PGE ores. Olivine tells especially of the very first stages of the crystallisation and deposition, which are also critical for the formation of a sulphide deposit. Moreover, the nickel content of olivine is high enough to be measured with required accuracy by electron microprobe. Besides olivine, the nickel content of ortho- and clinopyroxene and more rarely amphibole has been utilized, as well.

The nickel content of olivine and pyroxenes has to be studied against their Mg#, because fractional crystallisation of mafic silicates reduces the nickel content of the magma. Removal of sulphides with olivine will produce a steeper drop in nickel content, as will be shown in chapter 3.5. Since olivine is commonly altered, the nickel and copper contents of the whole-rock studied against MgO content, has been used mainly in komatiites (e.g. Kambalda, Naldrett 1989). This method is not as accurate as olivine analyses.

Table 3. Nernst partition coefficients between minerals and silicate liquid in natural and experimental mafic systems. For monosulphide solid solution (Mss) partition coefficients are between Mss and sulphide melt.

Element	Olivine	Orthopyroxene	Clinopyroxene	Amphibole	Sulphide	Chromite	Mss-
							Sulphide
Ni	1-40	1-6	1-6	6-16	100-700	5-20	1.0
Cu	0.02-0.2	0.1-0.4	0.07-0.4	0.05	180-1380	0.2-4	0.2
Co	1-5	1-2	1-2	0.5-2	30-100	3	0.9
Zn	0.9	0.4	0.5	0.4-10	0.1-1.1		
V	0.06-0.3	0.5-3	0.2-6	1.5-3	0.6	40	
Mn	0.5-1.3	1.2-2.5	0.5-2	0.9-2.9	0.06-1.8		
Pb	< 0.02	< 0.2	< 0.2	0.1	2-10		
Os	2				$10^2 - 10^5$		5
Ir	2-3				$10^3 - 10^5$		5
Ru					$10^3 - 10^5$		5
Rh	<<1				$10^3 - 10^5$		3
Pt	<<1	<<1	<<1		$10^3 - 10^5$		0.10
Pd	<<1	<<1	<<1		$10^3 - 10^5$		0.10
Au	<<1	<<1	<<1		$10^3 - 10^5$	<<1	0.10
Tl					>>1		
Se							0.9
As							0.01
Sb							0.18
Ag							0.1

Data sources: Mainly from the reviews by Lesher and Stone (1996) and Barnes and Maier (1999). Additional data from Paster et al. (1974), Bougault and Hekinian (1974), Canil (1999), Matsui et al. (1977), Dostal et al. (1983), Hart and Dunn (1993), Takahashi (1978), Pedersen (1979), Villemant et al. (1981), Duke (1976), McKenzie and O'Nions (1991), Hauri et al. (1994), Beattie (1993), Arndt, N.T. (1977), Ringwood (1970), Sisson (1994), Skulski et al. (1994), Ewart et al. (1973), MacLean and Shimazaki (1976), Shimazaki and MacLean (1976).



Element Co Cu X Ni Pd Figure 3. Concentrations of elements (value) in silicate magma (M, solid lines) and in sulphide liquid (S, dashed line) in

of elements (value) in silicate magma (M, solid lines) and in sulphide liquid (S. dashed line) in batch equilibration as a function of different silicate liquid to sulphide liquid mass ratios (logR). Composition of parental liquid is E-MORB (Table 4). The palladium content of the model liquid has been set higher than in E-MORB, at 10 ppb, to illustrate the Pd rich case relevant in the formation of PGE ores. Partition coefficients as in case A of Table 5.

Duke and Naldrett (1978) made a computer simulation of the fractionation of komatiite magma containing different proportions of olivine and sulphides. Naldrett (1989) describes several examples where the Ni depletion is well indicated in the Ni-MgO diagrams depicting compositional trends of sulphide-saturated and unsaturated peridotites.

Barnes et al. (1993) has used the Pd/Cu ratio of cumulates in identifying PGE depletion. Pd/Cu is very sensitive in sulphide segregations with a high R, as can be seen in Figure 3. Potentially any PGE to base metal ratio would describe the same, but Barnes et al. (1993) selected Pd/Cu because both elements are mainly bond in sulphides and their analysis is more reliable than others to consider.

The application of Cu/Zr ratio in identification of sulphides segregation is based on highly incompatible nature of both Zr and Cu in the absence of sulphides. Cu/Zr ratio changes significantly only by removal of sulphides. This method has been used by Maier et al. (2003) in the evaluation of PGE potential in Southern African flood-type basalts and MORB. Kerr (2003) used the Cu/Zr ratio in the evaluation of the base metal depletion and sulphide segregation history of the gabbroic intrusion in the Pants Lake area, Labrador. The method has been recently reviewed by Naldrett (2004).

Besides the analyses mentioned above, the use of thallium (Ikramuddin et al. 1983, McGodrick et al. 1979) and europium (Lodders 1996 and Dickinson et al. 1991) have been suggested to use to indicate sulphide segregation.

Chalcophile element depletion has been used in province, area and target selection as well as in localization the ore in two ways. Firstly, it has been used to indicate whether a sulphide segregation has taken place. Secondly, they can be used to evaluate, whether the possible sulphides are Ni-Cu-Co-PGE-rich or not. Provinces and areas, where some of the targets display chalcophile depletion and some not, have been regarded as potential ones e.g. in Kambalda and komatiite belts of the Fennoscandian Shield (Naldrett 1989). The same principle has been applied in target selection: targets showing variable chalcophile element depletion have been regarded the most promising ones (e.g. Svecofennian intrusions, Peltonen 1995d). Overall chalcophile depletion of the target has been mainly interpreted as a non-favourable indicator, while the opposite feature i.e. no signs of chalcophile element depletion, has not been interpreted as strongly. The potential chalcophile element content of sulphides due to a different R factor and primary magma composition has been evaluated on the basis of olivine composition, and the least chalcophile element depleted targets have been regarded as the most potential ones (Thompson and Naldrett 1984). Within the target the exploration activity has been directed in nondepleted parts, which have been interpreted to form earlier than the chalcophile-depleted part.

3.4 Sulphide accumulation, solidification and subsolidus re-equilibration

The final step in the formation of sulphide Ni-Cu ore is the concentration of sulphides in a restricted locality to form a deposit of economic grade and volume. An accumulation process is driven by gravity and magma flow dynamics. The co-precipitating phase is practically always olivine. Since sulphide is still molten and denser than olivine, ideally a sequence of billiard-ball model will form (Naldrett 1973): Massive sulphides on the bottom are overlaid by nettextured ore, in which the olivine cumulus minerals are enclosed in a sulphide network. The sulphide content decreases upwards leading to a disseminated ore and barren olivine cumulates at the top of the sequence. Massive sulphides are ideally located at the bottom of the intrusion or extrusion, and more specifically in embayments and other depression structures (e.g. Voisey's Bay, Evans-Lamswood et al. 2000). Quite often they are found in or close to the feeder dike or in another opening structure, where the speed of the magma flow has decreased resulting in suspended dense sulphide droplets with olivine to settle down.

Ni-Cu-Fe-PGE sulphide melt starts to crystallise above 1000°C with the appearance of Fe-rich monosulphide solid solution $Fe_{(1-x)}S$ -Ni_(1-x)S (*Mss*). Residual liquid at 1000 °C is enriched in Ni and Cu with respect to *Mss*, but at 850 °C the residual liquid is enriched in Cu and depleted in Ni with respect to co-existing *Mss*. This is because the partition coefficient of nickel, D_{Mss/sulf-liq}, is in tholeiitic systems close to one and increases as the temperature lowers (Barnes and Maier 1999, Craig and Kullerud 1969). In fractional crystallization, Mss is thus enriched in Ni, Os, Ir, Ru and Rh and the remaining sulphide liquid rich in Cu, Ag, Au, Pt and Pd, will solidify much later at temperatures below 800°C. In the ore deposit the fractional crystallization of the sulphide melt may lead to metal zonation where the main mass is *Mss* derived and enriched in Ni. Os, Ir, Ru and Rh relative to the residual melt derived Cu, Ag, Au, Pt and Pd sulphides, which may locate as overlaying dissemination or veinlets in the substrate. This type of zonation is found at Noril'sk-Talnakh region orebodies (Distler et al. 1977, Naldrett at al. 1994, Zientek et al. 1994), Sudbury offshoot ores (Li et al. 1993), and Bushveld (Barnes and Maier 1999). Finally both Mss and remaining sulphide melt crystallise to form the pyrrhotite-pentlanditechalcopyrite assemblage via complex subsolidus reactions.

In cooling, the sulphides will re-equilibrate with the other minerals present in the ore, mainly olivine and less with chromite and pyroxenes. The distribution of nickel between the sulphide melt and olivine has been studied experimentally and from natural deposits (Häkli 1963; Rajamani and Naldrett 1978; Boctor and Yoder 1983; Fleet and MacRae 1983, 1987; Thompson and Barnes 1984; Fleet and Stone 1990; Brenan and Cagiagli 2000). Binns and Groves (1976) observed that iron-nickel partitioning between the olivine and sulphide re-equilibriate in metamorphism, and the value of equilibrium constant:

$$K_{D_{(N-Fe)}}^{sulfide / olivine} = \left(\frac{NiS}{FeS}\right)_{sulfide} / \left(\frac{NiO}{FeO}\right)_{olivine} \quad (Equation 7)$$

increases, resulting in an increase in the nickel content of sulphides and the Fe content of the olivine with respect to magmatic equilibrium as shown by model calculations in Figure 4. This has to be taken into account, when considering the compositions of sulphides and mafic silicates.

Barnes (1999a) studied chromites of Jinchuan fertile intrusion and related barren ones. He noticed that due to re-equilibration with sulphides, the chrome-spinels in the ore zone are unique in composition with high Cr and Fe³⁺ and a low Ni content and Ni/Fe³⁺ ratio.

In nickel sulphide ore exploration, special

attention has been paid to the primary basal parts, feeder zones, channelised flows and depression structures of igneous bodies. They are revealed with the aid of olivine cumulates, which can be discovered with normal geological mapping tools and geophysical exploration methods. Olivine alters in retrograde metamorphism readily to serpentine + magnetite, which causes the olivine cumulates to be magnetic. When unaltered, olivine cumulates are denser than the rest of the igneous body. Massive ore differs notably from barren olivine cumulates in density, magnetic and conductivity. susceptibility Therefore. geophysical methods prevail in the exploration of Ni-Cu-rich sulphide accumulations (e.g. Pietilä 1991). In komatiites the fertile channelised flow environments can be identified in detailed geological mapping and also by applying the Cr vs. Cr/Ni plot (Brand 1999 and Barnes and Brand 1999) as already discussed in chapter 3.1.



Figure 4. Model calculations on the compositional shift of the olivine and sulphide fraction in re-equilibration in an olivinesulphide system. In the initial stage, the olivine and sulphide have fractionated from the basaltic liquid with $K_D=10$, Fo = 88%, Ni of olivine = 2100 ppm and the Ni tenor = 11.5%. Re-equilibrated composition is dependent on exchange partition coefficient K_D and the relative mass ratios of olivine and sulphide. <u>a</u>) Nickel content versus forsterite olivine content (sulphide = 100- olivine). In re-equilibration with sulphides, the nickel content of olivine decreases if the K_D reduces. Forsterite content remains almost constant. <u>b</u>) Nickel tenor, i.e. the Ni content of sulphide fraction, increases in the re-equilibration with olivine if the K_D increases.

3.5 Chemical composition of sulphides – introduction of nickel and cobalt numbers

Sulphide fraction of nickel ore consists mainly of five elements: sulphur, iron, nickel, copper and cobalt. There is a wealth of information on Ni/Cu ratios and PGE tenors of different kind of nickel deposits (e.g. Naldrett 1989, 2004), but the cobalt tenors have been largely omitted. In other contexts, the Co/Ni ratio has been incidentally used for identification of the rocks belonging to a certain igneous suite of differentiation (Fleisher 1968). Huhma (1970) found that the Co/Ni ratio changes in the vicinity of Outokumpu-type ores, which were utilised in the exploration.

The chemical composition of the sulphide fraction of the mafic-ultramafic rock in terms of nickel, copper and cobalt is controlled by: 1) chemical composition of the parental magma, 2) stage of the sulphide segregation, 3) the R factor, i.e. silicate – sulphide melt ratio, 4) ratio of fractionating sulphide liquid and silicates, 5) partition coefficients of nickel, copper and cobalt between the sulphide liquid and silicate melt, 6) fractionation of the sulphide melt, 7) postmagmatic equilibration of sulphide and silicate phases, and 8) low-temperature processes like alteration and mobilisation.

Typically, the variations of nickel, copper and cobalt are illustrated in a ternary diagram like that presented in Figure 5a. The order of the elements varies from one author to another. Although the ternary diagram is visually effective, the exact location and variance of data points are difficult to outline in the graph. For that purpose the Ni-Co-Cu ternary is divided into two new indices, which also reflect geological processes. The nickel number, marked as Ni#, describes the location of a point as projected from the cobalt apex to Ni-Cu side, and is defined:

$$Ni\#=100*\frac{Ni}{Ni+Cu}$$
 (Equation 8)

The cobalt number, marked as Co#, describes the distance from the Ni-Cu side:

$$Co #= 100 * \frac{Co}{Ni + Cu + Co}$$
 (Equation 9).

The concentrations of the elements in the equations 5 and 6 are in weight percent. Both nickel and cobalt numbers are without units and the %-mark is not used. If not otherwise stated, the Ni# and Co# refer to the composition of sulphide melt or sulphide fraction in the solid rock. When referring to the other phases, e.g. silicate melt, olivine or whole-rock composition, then it is clearly stated (e.g. Ni# of olivine, Co# of the rock).

In this study the Ni# and Co# are mainly depicted in x-y diagrams, where the Ni# is placed on the x-axis and the Co# on the y-axis. To mimic the Ni-Co-Cu ternary the x-axis is reversed and values increase from right to the left as shown in Figure 5b. Another reason for reversing the xaxis is to show the fractionation path of mafic silicates in sulphide undersaturation logically from left to right.

The Co, Ni and Cu concentrations of silicate liquid are controlled by the primitive character of the magma and fractionation of sulphides and mafic silicates. Komatiitic magmas have a high Ni/Cu ratio and the Ni# of the magma is generally greater than 85 increasing with MgO content (Figure 6, note that in this paragraph the Ni# and Co# of the silicate melt are discussed). In picritic melts the Ni# of the silicate melt is between 80 and 90, and in basalts below 80, respectively. The more primitive the magma, the lower the Co# of the magma. In komatiites the Co# of the silicate liquid is normally between 4 and 10 and in picrites 6-15. In basaltic melts the Co# of the magma is commonly between 10 and 15. The general trend of Figure 6 with smoothly increasing Co# along with a decrease in Ni# shows the fractionation of olivine.



Figure 5. Illustrating the Ni-Cu-Co ratios of sulphides in <u>a)</u> ternary diagram, and <u>b)</u> Ni# – Co# diagram. Same data from Bruvann in both pictures.





Ni# = 100 * Ni/(Ni+Cu) and Co# = 100 * Co/(Ni+Cu+Co).

Data from the Georoc database (http://georoc.mpch-mainz.gwdg.de/geo-roc/Start.asp), precompiled csv files on basalt tholeiites, boninites, komatiites, picrites and tholeiites on 10th September 2005.

In order to study the Ni#-Co# systematics in the fractional crystallisation of mafic magma, a modelling program called ApeModel was developed (Aarnisalo et al. 1999). E-MORB was selected for the basic case in the modelling, because its composition is fairly close to the parental magmas of the studied intrusions and is also well known in regard to trace elements. Chemical composition of the E-MORB is given in Table 4. A general crystallisation sequence of the E-MORB in conditions corresponding to a shallow crust was defined on the basis of the evolution of the liquid composition in the diopside-anorthite-quartz-forsterite using the phase relations of Irvine (1970, 1979) and Irvine et al. (1983). According to the created model, olivine alone crystallises from the E-MORB until about 6% of the melt has crystallised and the MgO content has decreased to 9.4 wt.%. This is followed by a short period of olivine and clinopyroxene co-crystallisation until the MgO content has decreased to 8.6 wt.%. From there on, clinopyroxene and plagioclase crystallise together.

Estimates of the partition coefficients of nickel, copper and cobalt between sulphide and silicate melts vary widely as shown in Table 3. For cobalt the values are normally between 10 and 100 and for nickel and copper between 100 and 1000. Partition coefficients are dependent on the chemical composition of the melt, temperature, pressure, oxygen and sulphur fugacities, and for all of these elements they increase with a decreasing magnesium content and temperature.

According to the literature review, the partition coefficient of cobalt is lower than that of nickel and copper in all-natural magmatic systems. The majority of the values observed from the volcanites have a D_{Co}/D_{Ni} of around 0.038-0.053, but in experimental data, the D_{Co}/D_{Ni} is 5-10 times higher, at around 0.3. In komatiitic and

other high magnesium magmas the partition coefficient of copper is normally higher than that of nickel (Ross and Keays 1979, Rajamani and Naldrett 1978, Naldrett 1989, Figure 7). Experimental studies of basaltic system reveal the sulphide-silicate partition coefficient of nickel is higher than that of copper, but in a komatiitic system (Gaetani and Grove 1997) and in volcanic rocks, where the determinations have been made from sulphide droplets, the partition coefficient of copper is quite often higher than that of nickel (Francis 1990, Peach et al. 1990, Jana and Walker 1977). Consequently, model runs were made with three different partition coefficient values as given in Table 5. In the first set of runs (labelled A) the partition coefficients between the sulphide and silicate liquids correspond to basaltic liquid, where the order from the smallest to the greatest is D_{Co}<D_{Cu}<D_{Ni}. In the second and third set of runs, labelled B and C, the order of the partition coefficients is D_{Co}<D_{Ni}<D_{Cu}, and the values of the partition coefficient correspond to two types of komatiitic melts as given by Naldrett (1989).

Table 4. Composition of E-MORB from the FAMOUS area (Langmuir et al. 1977) used in the base case modelling and estimated parental magma compositions of the case study intrusions.

SiO2 wt.%	48.4	MnO wt.%	0.15	S ppm	300	Mg#	69.7
TiO ₂ wt.%	0.81	MgO wt.%	11.2	Co ppm	51	Ni#	76.4
Al ₂ O ₃ wt.%	15.3	CaO wt.%	11.8	Ni ppm	262	Co#	12.9
Cr ₂ O ₃ wt.%	0.085	Na ₂ O wt.%	1.84	Cu ppm	81	Al ₂ O ₃ / TiO ₂	18.9
FeOtot wt.%	8.66	K_2O wt.%	0.07	V ppm	167	CaO/ Al ₂ O ₃	0.77

Table 5.	Partition	coefficients	between	minerals and	l silica	te liquid us	ed in mo	delling	g. D val	lues (le	ft) and	equation	ons (ri	ght) for	r E-
MORB	between 1	MgO 11.2→	9 while c	olivine is the	e only	fractionati	ng phase.	MgO	refers	to the	MgO o	content	of the	melt.	For
mono-su	alphide so	lution (Mss)	the partit	ion coefficie	nts are	between t	ne Mss ar	nd sulp	hide m	elt.					

Element	D_{Ni}	D_{Cu}	D_{Co}	Eq. Ni	Eq. Cu	Eq. Co
Olivine-silicate liquid	8→12.5	0.03	2.9→3.6	3.346*MgO-3.664 (1)	0.03 (2)	0.786*MgO-0.385 (1)
Orthopyroxene-silicate liquid	3.4→3.9	0.13	1.6→1.8	1.206*MgO-0.263 (1)	0.13 (3)	0.467*MgO+0.14 (1)
Clinopyroxene-silicate liquid	1.1-1.5	0.08	1.36-1.41	$0.131*D_{Ni}^{Ol}(4)$	0.08 (3)	(exp(2.375-0.668* log(MgO)))/3.6 (2)
Sulphide-silicate liquid	A=275 B=175 C=100	250	A=80 B=58 C=40	-	-	-
Mss-sulphide liquid (5)	1.0	0.2	0.9	-	-	-

References: (1) Beattie et al. 1991, (2) Duke and Naldrett 1978, (3) Hanski and Koivumaa 1983, (4) From this study (average of the values given in Table 24), (5) Barnes et al. 2001.





Figure 7. Literature survey of partition coefficients between sulphide melt and silicate melt. Besides experimental data figures include data, which has been deduced from basic volcanites (observed), estimated using the data availabe (Estimate) and estimates from the concentrations analysed in ore deposit (ore deposit).

<u>a)</u> Partition coefficient of Cu *vs.* Ni between sulphide melt and silicate melt from literature. Line k=2.0 (y=k*x) fitted through the data points of Loucks (1990), Czamanske and Moore (1977), Francis (1990) and Cowden and Woolrich (1987). Line k=0.35 fitted through the experimental data points of Gaetani and Grove (1977). Line k=1 drawn for reference.

b) Partition coefficient of Co *vs.* Ni between sulphide melt and silicate melt.

c) Box and whisker diagram of variation in partition coefficient of Co, Cu and Ni between sulphide melt and silicate melt. Median values: Co 58, Cu 500, Ni 525. Data sources: 1 Gaetani and Grove 1997; 2 Loucks 1990: 3 Rajamani and Naldrett 1978; 4 Naldrett 1979; 5 Sargsyan 1985; 6, 9 and 14 Peach et al. 1990; 7 Klöck and Palme 1988; 8 Francis 1990; 10 Li and Naldrett 1994, 11 Francis 1990; 12 Jana and Walker 1997; 13 Cowden and Woolrich 1987; 15 Pedersen 1979; 16 MacLean Shimanzaki 1976; 17 Duke and Naldrett 1978; 18 Hanski and Koivumaa 1983; 19 Naldrett 1989; 20 Ross and Keays 1979; 21 Campbell and Naldrett 1979a, 1979b; 23 Czamanske and Moore 1977; 24 Skinner and Peck 1969; 25 Fleet et al. 1977; 26 Fleet et al. 1981.

At first the batch segregation of sulphide melt alone from E-MORB is studied using equation 2. The Co# and Ni# of the segregating sulphide liquid depend on the sulphide to silicate melt mass ratio, R factor, and on partition coefficients as shown in Figure 8a and Figure 9. If the R factor is high, the Co# is low. The higher the amount of segregating sulphides, the lower the R factor is and the closer are the Co# and Ni# of the sulphides to the Co# and Ni# of the silicate liquid (Figure 8a). For example, in the modelled E-MORB case, the Co# of segregating sulphides is about 4.2 when the amount of sulphides is infinitely small ($R>10^5$). As the amount of sulphides increases, the Co# increases reaching a value of 7-8 when R is 100 and finally that of the

silicate melt, 12.7, when R is 1 (Figure 8a and Figure 9). The Ni# of the sulphides is dependent on partition coefficients, as shown in Figure 8a. When $D_{Ni} > D_{Cu}$, as in case A, the Ni# of the sulphides is greater than the Ni# of the silicate liquid in equilibrium, whereas in cases B and C, where $D_{Ni} < D_{Cu}$, the Ni# of the sulphides is less than the Ni# of the parental liquid. Whether the sulphides derive from the magma or an external

source does not make any significant difference in the Ni#-Co# systematics, though the equation of equilibration is different (Equation 2 versus Equation 3). If the assimilant is metal-bearing, then the differences are like in the cases where the silicate melt composition of nickel, copper and cobalt are different: thus the starting point is different but trends equal the cases discussed above.



Figure 8. The Co# versus Ni# plots illustrating the composition of segregating sulphides from the E-MORB with three different partition coefficients as given in Table 5. Ni#=100*Ni/(Ni+Cu) and Co#=100*Co/(Ni+Cu+Co). **a**) Batch segregation of sulphides. LogR plotted next to the data points. **b**) Fractional removal of crystallising olivine with an infinitely small amount of sulphide (100*sulphide/(sulphide+olivine)=1 ppm) drives the sulphide composition towards a lower Ni# and a slightly higher Co#. The starting points of the batch *vs.* fractional segregation cases, e.g. A_{batch} *vs.* A_{fractional}, are equal.



Figure 9. Comparison of <u>a)</u> nickel content of olivine and <u>b)</u> Co# as a function of R factor (silicate to sulphide mass ratio) in batch equilibrium.

The continuous fractional segregation of crystallising olivine with an infinitely small amount of sulphides decreases the Ni# of sulphides significantly and increases the Co# slightly, as shown in Figure 8b. The starting points of Figure 8a and b are the very same, but the directions of the trends are clearly different.

Term *SCS*, sulphide content of the segregate, i.e. the ratio of sulphide to all segregated phases, is defined:

$$SCS = 100 * \frac{m_{sulphide melt}}{\sum_{i=1}^{n} m_i}$$
 (Equation 10),

where m refers to mass and *i* to segregated phases and *n* is the number of phases. Normally in the nickel sulphide ores segregate consists of olivine and sulphide, n=2, and SCS varies from 0.25 to 2 (Naldrett 2004).

The net effect of the fractional segregation of olivine and sulphide liquid is studied in Figure 10a-c, where the SCS, ranges from 1 ppm to 99. In all the cases with different partition coefficients (A. B and C) the fractionation of olivine with a small amount of sulphides produces an evolution trend, where sulphide composition moves to a lower Ni# while the increase in the Co# is only minor. As the SCS value increases, the Co# starts to increase and the evolution trend becomes steeper. When $D_{Ni} >$ D_{Cu}, as in case A in Figure 10a, the Ni# decreases in all the sulphide to olivine ratios. When D_{Ni}<D_{Cu}, as in cases B and C (Figure 10b and c), the increase of sulphides content in respect of the olivine causes a tendency to shift form, decreasing Ni# to increasing Ni# and Co# as shown in Figure 10b and c.

Figure 11 depicts the change in the nickel content of olivine in comparison to Co# in the fractional segregation of olivine and sulphide melt.

The Co# of sulphides increases significantly only if the sulphide melt is removed from the system, while the nickel content of olivine also decreases in the fractionation of olivine only. Therefore, the application of olivine nickel content to indicate sulphide fractionation, involves the comparison of nickel content of the olivine with forsterite content, while the Co# can be used alone (Figure 11) The relationship between nickel and forsterite content of the olivine is very sensitive to even small changes in the sulphide to olivine ratio, especially if the SCS is >1, as shown in Figure 10e. The Co# increases considerably only when the SCS is of a magnitude of 5 (Figure 10a-c). The segregation of sulphides can be identified positively in fractional and batch process from the Co#, when the total content of fractionated sulphides exceeds 0.7% (the content of silicate liquid is 100% in the beginning of fractionation), as shown in Figure 11c. Please note that the R factor and the total amount of sulphides are not synonyms, since the R factor refers to a silicate melt sulphide melt ratio in a batch equilibration, while the latter refers here to fractionation process. In order to have a common measurement for the ratio of sulphide melt and total amount silicate magma in all processes the term SS, total amount of sulphides segregated, is used:

$$SS = 100*\frac{m_{sulphides}^{segregated from the system}}{m_{sulphides}^{Total}}$$
(Equation 11),

where m is mass. In batch segregation SS and R factor are related as follows: SS=100/(R+1).

It is also interesting to note that a batch segregation process cannot produce higher Co# than that of the parental liquid, while fractional crystallisation may produce much higher Co# already when the SS reaches 1%.

Figures 7 to 10 illustrate the composition of the sulphide melt once it has separated from the silicate liquid with or without olivine. However, during cooling the monosulphide solid solution, *Mss*, may fractionate from the sulphide melt, as discussed above in chapter 3.4, causing changes in the Ni# and the Co#. The partition coefficients of Ni, Co and Cu between monosulphide solid solution and the sulphide liquid used in modelling were taken from the estimates of Barnes et al. (2001), and are given in Table 3. The composition





Distribution coefficient between

sulp	hide liquid a	and silicate n	nelt
	Ni	Cu	Co
А	275	250	80
В	175	250	58
С	100	250	40

Figure 10. Evolution trends of sulphide liquid (a-c), silicate melt (d) and olivine (e) in the fractional segregation of olivine and sulphide melt from the model E-MORB with various *SCS* values (i.e. 100*sulphide/(sulphide+olivine), numbers in the legend). Partition coefficients of Ni, Co and Cu correspond to cases A, B and C in Table 5. In cases SCS = 1ppm-25.0 the length of the path corresponds to the development of the liquid from 11.4 to 8 wt.% MgO, which is equal the crystallisation of 12-16 wt.% of magma. Each dot represents ca. 0.5 wt.% removal of phases, except in cases 25 and 50, where the dot interval is 0.1 wt.% removal of phases and in 100 wt.% it is 0.05 wt.%. Numerical modelling done with the ApeModel program.



of fractionating *Mss* is in terms of Ni# and Co# close to the composition of the initial sulphide melt, but the residual evolves towards a lowering Ni# and Co# as depicted in Figure 10a.

Commonly Ni-Cu deposits are associated with chalcopyrite-rich veins adjacent to the ore and within the country rocks beneath the intrusion. If the veins are a product metamorphic chalcopyrite remobilisation, the residual sulphides will enrich in Co# and especially in Ni# (Figure 12b).



Distribution coefficient between

Sulphide liquid and silicate men						
	Ni	Cu	Co			
А	275	250	80			
В	175	250	58			
С	100	250	40			
_						

Figure 11. Evolution of Ni content of olivine and sulphides Co# in fractional segregation of olivine and sulphide melt from the model E-MORB. <u>a)</u> Co# vs. Ni content of olivine, cases A, B and C. <u>b)</u> The nickel content of olivine and <u>c)</u> the Co# of sulphides versus the SS%, percentage of sulphides removed compared to the amount of initial liquid. The nickel content of olivine decreases as a result of olivine fractionation while the Co# of coexisting sulphides increases significantly only when also the sulphides are removed. A, B and C, refer to different partition coefficients used in modelling (Table 3). The numbers in b refer to the SCS value, i.e. 100*sulphide/(sulphide+olivine).

The average compositions of selected Ni-Cu and PGE deposits are presented in the Co# vs. Ni# diagram in Figure 13. They all display Co#<5, and therefore represent sulphide segregations from primitive magmas. Komatiitic nickel ores have a high Ni#, >90 and a low Co#, Protorozoic komatiitic <2. Ni deposits (Donaldson West and Katiniq) have a lower Ni#, ca. 80, but similar Co# as the Archean



Figure 12. Evolution of the chemical composition of sulphides Co# vs. Ni# diagram in <u>a</u>) fractional removal of monosulphide solid solution (Mss) from a sulphide liquid and <u>b</u>) removal of chalcopyrite (Ccp) from the sulphide melt. In both figures the percentage of fractionation is shown in numerical form.

counterparts. The picritic Pechenga deposit has a still lower Ni#, 70, but the Co# is as low as in the komatiitic deposits. Deposits associated in gabbroic intrusions display Ni# typically between 60 and 80 and Co# between 3 and 4.5. Svecofennian nickel deposits (Kotalahti, Makola, Stormi, Kylmäkoski, Laukunkangas), Montcalm and Voiseys Bay Eastern Deeps are included in this group. Sudbury ore bodies form a pattern that can be expected in a deposit subject to *Mss* or chalcopyrite fractionation, as discussed above (Figure 12). PGE deposits (Bushveld and Penikat) and those associated in flood basalts (Noril'sk, Insizwa, Minnimax and Great Lakes) display low Ni#, 15-55, associated with a low Co#, <2.

The Co# and Ni# of the Ni-Cu ore deposits presented in Figure 13 confirm that the features modelled and discussed previously in this chapter are to be found in nature, and Co# and Ni# used together serve as a potential tool to be used in classification ore deposits and exploration of sulphide Ni-Cu-PGE ores.

In this study the identification of Ni and Cu depletion from the cumulate samples is an essential factor, for which the Co# is mainly used. Because the intrusions studied have crystallised from basaltic-picritic magma, it is possible to set uniform limits for the depletion. An intrusion, a part of it or a sample is said to be <u>undepleted</u> when it has crystallised from base metal undepleted magma indicated by its low Co#, <10. Analogously, if its Co# is 10-30, the term <u>depleted</u> is used and <u>extremely depleted</u> when the Co# is >30. Similarily, the Ni# is used to describe the primitiveness of the magma. The conclusion is made from the most undepleted samples. If Ni# is >75 an intrusion, a part of it or a sample has crystallised from MgO rich, primitive magma, and it is called <u>primitive</u>. The term <u>moderate</u> <u>primitive</u> is used when Ni# is 50-75 and <u>evolved</u> when the Ni# is <50.

Figure 14a summarises the evolution trends of Ni# and Co# in magmatic and postmagmatic processes. Consequently, different kinds of distribution patterns are to be expected when plotting Ni# vs. Co# values of the mineralised and barren mafic-ultramafic cumulates, as depicted in Figure 14b. Fractionation of olivine alone from base metal undepleted magma will produce a pattern of decreasing Ni# with a smoothly increasing Co# (field 1 in Figure 14b). A similar trend is expected, but higher in Co#, if the

34 Geological Survey of Finland Bulletin 402 Pertti Lamberg

parental liquid is a base metal depleted due to earlier sulphide segregation. Fractionation of sulphides will produce steep trends as shown in fields 3 and 4 in Figure 14b. Samples with highest Co# are located furthest away from the ore (field 0). If the sulphide fractionation pattern exists with low Ni# (field 5), the parental liquid is highly evolved and sulphides will be rich in copper and low in nickel. Although patterns 3, 4 and 5 require sulphide segregation; they will not indicate anything about the accumulation process, and both formation of disseminated and massive ores would produce similar patterns. Pattern 6, however, is expected to be found only in the intrusions which host sulphide accumulation, since this distribution requires a fractionation of the sulphide melt or mobilisation of chalcopyrite veins, which should be common in disseminated ores.

Although Ni# and Co# are new indices and

they have not been used previously in the way used in this study, the mutual ratios of Ni, Cu and Co have been used widely in characterising the magma, intrusion and ore types. Ni to Cu ratio is frequently used as the basic property of the ore variation in the ratio indicates and the fractionation crystallization of sulphide liquid. Cobalt has mainly been omitted. Häkli (1963) found that the Ni/Co and Ni/Cu ratios decrease with the increasing silica content of igneous rocks. Makkonen and Ekdahl (1984) used the Ni/Co ratio together with the Ni content of olivine sulphide interpret the saturation to and segregation history of the Koirusvesi intrusion. Merkle and Von Gruenenwaldt (1986) found that in the Upper Zone of the Bushveld Complex, South Africa, Ni depleted rocks contain Co-rich pentlandite, and the high Co/Ni ratio of pentlandite is reflected also in coexisting pyrrhotite as well as in whole-rock composition.



Figure 13. Composition of selected Ni-Cu deposits Co# versus Ni# diagram. Upper field delimits the ores in the Svecofennian mafic-ultramafic intrusions (SMUI), the lower field is for Sudbury ores. 1-Langmuir No.2, 2-Langmuir No.1, 3-McWatters, 5-Epoch mass, 7-Shangani mass, 9-Trojan mass, 26-Donaldson West, 27-Katiniq, 28-Pipe, 31-Levack West: Main ore, 32-Levack West: Cu-rich stringers, 33-Strathcona, 34-Strathcona: Cu zone, 35-Little Stobie 1, 36-Stobie 2. 37-Little Falconbridge, 38-Montcalm, 40-Pechenga, 41-Kanichee, 42-Kenbridge, 43-Minnmax, 44-Great Lakes, 45-Insizwa (excl.

Cu rich), 48-Talnakh komsomolsky, 53-Bushveld Platreef Upper, 54-Bushveld Platreef Lower, 57-Eastern Deeps, 58-Ovoid, 61-Hyvelä, 76-Makola, 77-Kotalahti, 81-Kylmäkoski, 84-Stormi, 85-Laukunkangas, 132-Kuusijärvi, 133-Porttivaara, 194-Ban Phuc. 1-54 from Naldrett (1989), 57-58 from Naldrett 2004, 61-85 from Puustinen et al. (1995) and 194 from Glotov et al. 2001.



Figure 14. a) Summary of the effect of different processes on the composition of sulphide liquid in equilibrium with silicate liquid in Co# vs. Ni# diagram. Primarily composition of the sulphide melt in equilibrium with primary basaltic magma is indicated by the grey ellipse. Exact values of Ni# and Co# depend on magma composition and partition coefficients of Ni, Cu and Co. Fractionation of olivine will cause coexisting incremental sulphides to plot along the olivine fractionation trend, -OI. Sulphide segregation will move the subsequent sulphide liquid to follow either trend A or B depending on partition coefficients If sulphides fractionate with olivine, the evolution trend will be between A and -Ol or B and -Ol. Fractionation of Mss from the sulphide liquid will move the Mss-rich fraction towards Mss -arrow and residual towards -Mss arrow. In the same manner the mobilisation of chalcopyrite-rich material will move the removed fraction towards Ccp arrow and residual towards -Ccp. b) Consequently different processes will produce different distribution patterns in solidified cumulates when plotted on a Co# versus Ni# diagram. Ni-Cu sulphide ore, which has not been subject to Mss fractionation nor chalcopyrite mobilisation should plot a pattern like the grev ellipse (0). A system, which has not been subject to significant sulphide segregation but is dominated by a fractional crystallisation of olivine, produces a pattern like field 1. Field 2 represents a body, which formed from chalcophiledepleted magma (due to earlier sulphide removal) by the fractional crystallisation of olivine. Field 3 is an example of a system produced by fractional sulphide ± olivine segregation. Partition coefficients of Cu, Ni and Co are typical for basaltic magmas. Field 4 represents system, which has been dominated by the fractional segregation of sulphides with partition coefficients typical of Mg-rich silicate melts. Field 5 shows the pattern expected in a system, which is highly evolved due to previous olivine fractionation, and late sulphide segregation. These sulphides are Cu-rich. Field 6 is a pattern expected in Ni-Cu ores subject to Mss fractionation or chalcopyrite remobilisation, or both.

4 METHODS AND TERMS

A full alphabetical list of the terms used with analytical data can be found on the appendix CD. definitions is given in chapter 20. All the

4.1 Sampling

Nine intrusions from four different geological environments and four countries were selected as case study targets in order to test the methodology (Table 6 and Figure 15). Three of the intrusions have been the subject of nickel sulphide mining and are termed <u>fertile intrusions</u>. Three are <u>subeconomic</u> Ni-Cu occurrences and three are proven to be <u>barren intrusions</u>, i.e. very unlikely that the intrusion would host any significant mineralisation, according to current knowledge.

Geological fieldwork done for this study is quite limited for most of the intrusions, but instead the work is done in the drill core logging, sampling and geochemical, and mineralogical studies of samples. Samples were collected from Bruvann in Norway and Laukunkangas, Stormi, Posionlahti, Rausenkulma and Ekojoki in Finland
(Table 6). Alter do Chão in Portugal was sampled by the nickel exploration team of Outokumpu Minera Española and Dr. Lauri Pekkarinen. The study of Porrasniemi is based almost entirely on data presented by Lamberg (1990). Only some isotopic determinations were done for this study. For the study of Rörmyrberget the work of Ylander (1997) was utilised and an additional ten ore samples were collected for this study. Data and samples collected previously in the Outokumpu databases were utilized in all the targets.

In this study the essential purpose is to develop methods to identify the presence of ore or mineralisation from samples that originate far from the ore. Therefore a clear distinction is made between ore samples and other samples. The ore samples are studied to uncover the origin of the ore, the ore forming processes which have taken place and their fingerprints. These specific

Table 6. Number	of	studied	and	analysed	samples.
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Target	Number of	samples	Sampled drill holes	Field work	Scientists participating in
-	Total	Collected	-	years	sampling and field work
		for this		-	
		study			
Bruvann	228	221	235-120, 235-160, 260-125,	1996-1998	T. Karppanen, T. Augé, R.
			260-140, 270-135		Pietilä, L. Storhaug
Stormi	816	53	TY-183, OK/VA-280, -328,	-	T. Augé
			-762, -927		-
Laukunkangas	798	73	EK/LA-25, -30, -38	-	T. Augé, L. Grundström
Ekojoki	142	17	VM/EJ-18, -17	-	T. Augé, P. Peltonen
Porrasniemi	69	0	-	1986-1990	P. Liukkonen
Rörmyrberget	229	10	-	1995, 1996	I. Ylander
Alter do Chão	222	0	-	1995	J. Jokela, J. Beck, L. Pekka-
					rinen
Posionlahti	260	26	VM/PSL-5	-	T. Augé, P. Peltonen
Rausenkulma	184	36	KKI/RAU-8, -14	1989	L. Grundström, J. Niemonen,
					Τ Δυσέ







imprints are then studied in other samples and compared to the ones from barren intrusions. <u>Ore</u> <u>samples</u> are defined as samples containing more than 0.5 wt.% Ni or Cu. This is not the best definition since there are also samples among mined ores, which do not fit this definition. However, because the data of ore polygons was not available, simple Ni and Cu grade thresholds were used for distinction. Also, a barren intrusion may contain *ore samples*. Samples with less than 0.5 wt.% Ni and Cu are called *barren samples* or *barren cumulates*. Again, Ni and Cu grades are not the best mean of discrimination, because it does matter whether the sample is derived close to or far from the ore. The spatial and stratigraphic relationship between the barren samples and the ore is taken into account.

4.2 Chemical analyses

Number of samples studied and analysed is given in Table 7. Chemical analyses were done mainly at the Geoanalytical Laboratory of Outokumpu Research (currently under the Geological Survey of Finland). The samples were crushed by jaw crusher and divided by a sample splitter, and one split was ground by ring mill to final analysis fineness. The concentrations of 40 main and trace elements were determined with Phillips PW 1400 X-ray fluorescence analyser from a pressed ground rock briquette using RRFPO (Rautaruukki Fundamental Parameters) correction program (Ala-Vainio 1986). Hydrous samples ($H_2O > 5$ wt.%) were ignited before the analysis. Leco analysers were used to determine carbon (Leco CR-12) and sulphur (Leco SC-32) content. Cu, Zn, Ni, Co and Fe incorporated in sulphides were analysed by a Perkin Elmer 5000 flame AAS after a selective bromine-methanol leaching (abbreviated as BM, Penttinen et al. 1977).

The characteristics of wall rock contamination, as well as the source of sulphur, were traced with an isotope (Sm/Nd, C, S) and trace element (REE, LILE, S-Se) geochemistry. Isotope analyses were made at the *Le Bureau de Reserches géologigues et minères*, BRGM, laboratories, Orléans, France. Graphite was analysed for carbon isotopes using a combustion method of graphite under oxygen atmosphere. Total sulphides were analysed for their sulphur isotopes using the method of Thode et al. (1953). Whole-rocks were analysed for oxygen isotopes by the fluorination method with a CO₂ laser (Fouillac and Girard 1996).

PGE analyses were done at *BRGM* using ICP/MS. Ekojoki analyses were provided by P. Peltonen and done at Geological Survey of Finland using Ni sulphide Fire Assay preconcentration, Te co-precipitation and ICP/MS, a technique described by Juvonen (1999).

Table 7. Number	of samples	studied	and	analysed.	Note,	that a	ı part	of	the	analyses	were	taken	from	the	Nickel	programme
database of Outoku	ımpu Minir	ng Oy and	d hav	ve not been	n done	for th	is stu	dy.								

Target	Chemical analyses				Isotope analyses				Thin	Miner	al analyses
	Whole-	Sulphide	REE	PGE	Sm/Nd	S	0	С	sections	Total	Trace Ni
Bruvann	222	221	12	8	9	11	6	6	226	302	222
Stormi	238	646	8	7	2				53	321	645
Laukunkangas	459	485	3	12					73	72	780
Ekojoki	128	131	15	4	1				17	89	113
Porrasniemi	67	62			2				67	101	68
Rörmyrberget	229	212		6					10	43	227
Alter do Chão	222	114							25	-	222
Posionlahti	132	255	2	2					26	118	132
Rausenkulma	101	184	2	3	1				36		101
TOTAL	1798	2310	42	42	15	11	6	6	533	1046	2510

* Selective bromine-methanol dissolution + AAS (Penttinen et al. 1977), sulphur by Leco.

4.3 Mineralogy

Polished thin sections were prepared from 439 samples. Mineral textures were studied and the normative cumulus name was checked and compared to the observed current and interpreted magmatic composition.

Mineral analyses were carried out by a Cameca SX-50 electron microprobe equipped with three wavelength dispersive spectrometers, secondary and backscattered electron detectors, and PDP 11/73 computer with Cameca software. The acceleration voltage for sulphides was 25 kV and current 25 nA, and for oxides and silicates 20 kV and 15 or 10 nA, respectively. Counting times for peak and background were 10 seconds. Synthetic oxides and minerals were used as standards. The Cameca PAP correction procedure was applied. Iron was analysed as total FeO and Fe reallocation for spinel was made using Droop's (1987) procedure. Amphiboles were named and

their formulas were calculated after the IMA scheme (Leake 1987) using an AMPHTAB FORTRAN program (Rock and Leake 1984, Rock 1987).

The Ni content of mafic silicates was SX-50 determined by Cameca electron microprobe integrating the Ni Ka intensities using the following procedure: acceleration voltage 35 kV, beam current 350 nA, beam diameter about 10 µm, six steps per peak integration area, and six seconds counting time per step. Background intensities were recorded from two different angles on both sides of the peak (totally 10 steps). A natural olivine with 2800 ppm Ni was used as a standard. The detection limit of the method is about 30 ppm and precision in the range observed (1000-4000 ppm) is about ± 30 ppm.

4.4 Analyses from the Nickel Programme database

A large number of analyses of the Outokumpu Nickel Programme database and the Outokumpu *NIXPLOR* database were utilised in this study (Häkli 1971). The samples were previously (between 1968 and 1997) analysed in the same laboratory and with the same methods than the samples collected for this study. The XRF device and correction programme were changed a couple of times during these years, and hence the number of analysed elements was less in the 1960s and 1970s. For some elements there are differences in assays obtained with different equipments and correction programs. For example, barium and rubidium analyses before 1996 are not comparable with more recent analyses. The differences were studied and taken into account in this study. The analysis procedure for trace nickel contents in mafic silicates has remained practically the same during the years, and analyses should be mutually very comparable.

4.5 **Processing of the chemical analyses**

Mineral assemblages of mafic and ultramafic cumulates subject to this study are in most cases at least partly of secondary origin. Original igneous chemical compositions of the rocks and minerals have changed in several stages. With the exceptions of the immediate contact zones, however, the system has in most cases been closed with respect to other elements except volatiles (H_2O , CO_2), and hence the volatile-free chemical composition of the altered rock is here considered the same as the original cumulate + trapped liquid system. On that basis, it is possible to calculate back the chemical composition of the bulk rock and weight percentages as well as

chemical compositions of different minerals. The methods, which were developed partly during the course of this study, are described in the following. Symbols used for calculation methods are given in Table 8.

In this study, data processing has been done using the ApeRock and ApeKraph programmes (currently known as *HSC Geo*). Since the chemical analyses were mutually comparable, normalization and normative calculations and data processing were done with one programme using a similar procedure, so the numbers presented here should be mutually consistent.

4.5.1 Composition of the sulphide fraction (SF)

The first step in the petrological calculations of mafic and ultramafic rocks is to determine the mineralogy and chemical composition of the sulphide fraction and to subtract it from the whole-rock composition for further calculations of sulphide and silicate fractions. Sulphides of mafic igneous rocks belong to the Fe-Ni-Cu-Co-S system. In addition to sulphides, significant amounts of the total contents of iron, nickel and cobalt are bound to silicates and oxides; consequently, the composition of the sulphide fraction is difficult to estimate reliably. Simplifications with fixed sulphur content of the sulphide fraction are in use (e.g. Grundström 1980, Kerr 2001 and 2003).

Several wet chemical methods have been developed for the determination of sulphide nickel (Czamanske and Ingamells 1970, Penttinen et al. 1977, Karapetyan 1968, Lynch 1971, Katsnel'son and Osipova 1960). Klock et al. (1986) tested six published analytical techniques for the selective chemical dissolution of sulphidebound nickel. They recommended the brominemethanol method (Penttinen et al. 1977) for assaying sulphide-nickel deposits in cases when nickel is also present in silicate phases. Brominemethanol leach attacks sulphides (except pyrite, of which only 7% is dissolved in brominemethanol) leaving silicates and oxides untouched. When bromine-methanol dissolution is used and chemical compositions of the sulphide minerals are known (determined by electron microprobe), it is possible to calculate the actual composition of sulphide fraction by applying the mass balance between different minerals (Lamberg et al. 1997).

,		5	1 1	8 1
Symbol	Meaning	Figures and tables	Text	How to read
XRF	X-ray fluorescence analysis	Ni#_XRF	Ni#_XRF	Nickel number calculated from X-ray fluorescence analyses
BM	Bromine-methanol dissolution + AAS analysis	Co#_BM	Co#_BM	Cobalt number calculated from analyses by bromine-methanol dissolution and atomic absorption spectrophotometry (AAS)
SF	Sulphide fraction	Ni_SF%	Nickel tenor	Ni content of the sulphide fraction in weight percentages
_n	Volatile- and sulphide-free composition	MgO_n%	<i>MgO_n</i> content	Volatile- and sulphide-free MgO content in weight percentages
VF	Volatile-free	Al ₂ O ₃ _VF%	Volatile-free aluminium content	Volatile-free aluminium content in weight percentages
CIPW	CIPW normative mineral content	Ol_CIPW%	CIPW normative olivine content	CIPW normative olivine content
BN	B-normative mineral composition	Phl_BN%	Normative phlogopite content	B normative phlogopite content in weight percentages
Δ	Delta value	ΔΝί	ΔΝί	Delta nickel, difference in the nickel content between observed and modelled/reference case
moln	Molecule normative composition	Pl_moln	-	Molecular normative plagioclase content

Table 8. Symbols used in connection with analyses and calculated quantities. Full alphabetic list is given in chapter 20.

If chemical compositions of sulphide minerals are not known, a simplification can be made on the basis of stoichiometric compositions. In this study the normative minerals of the sulphide fraction are: pyrrhotite (FeS), pyrite (FeS₂), $(Ni_{4.76}Fe_{4.24}S_8)$, chalcopyrite pentlandite (CuFeS₂), Co-pentlandite (Co_9S_8), arsenopyrite (FeAsS), sphalerite (ZnS), molybdenite (MoS₂) and galena (PbS). In calculation, all of the sulphidic base metals are allotted in a single phase as follows: lead in galena, molybdenum in molybdenite, zinc in sphalerite, arsenic in arsenopyrite, cobalt in Co-pentlandite, copper in chalcopyrite and nickel in pentlandite. The remaining sulphur and iron are balanced between pyrrhotite and pyrite. Equations and chemical composition of normative sulphide minerals are given in Table 9.

When the weight percentages of normative sulphides have been calculated, trace elements bound in sulphides: i.e. Os, Ir, Ru, Rh, Pt, Pd, Au, Re, Ag, Cd, Sn, Sb, Bi, Se, Te and Hg, if analysed, are added to the sulphides. Recalculation to 100% gives the mineral composition and trace element content of the sulphide fraction. From mineral abundances the chemical composition of the sulphide fraction is calculated as given in Table 9 (step 8).

If only bulk assays are available, the chemical composition of a sulphide fraction is calculated by setting the pyrite to zero and by following the guidelines given in Table 9. Since nickel and cobalt are also bound in non-sulphides, the calculation gives either too high a pentlandite and cobalt pentlandite and consequently Ni and Co content of the sulphide fraction, or residual sulphur ends up negative. In the latter case all normative sulphides are set to zero and S is allotted to pyrrhotite.

Though sulphides of a sample may also contain other sulphides than listed in Table 9 like cubanite, gersdorffite, different pyrrhotites (troilite, monoclinic and hexagonal), the result of the chemical composition of the sulphide fraction is more accurate and reliable than if fixed sulphur content were used. If the sulphide fraction is calculated from total analyses, then samples containing less than 2% sulphides must be treated with caution for the above-mentioned reasons.

The routine used gave normative pyrite in 46% of the samples (n=596), but in all of them normative pyrrhotite was present and only in six cumulate samples normative pyrite dominated over normative pyrrhotite (Figure 16). A microscopical check revealed that pyrite is present in very few samples. An overestimation of the normative pyrite comes most probably from the pyrrhotite composition, since the normative pyrrhotite used is FeS, while it actually is between FeS and Fe₇S₈. According to the normative pyrrhotite to pyrite ratio, the average composition of pyrrhotite is Fe_{0.903}S. Whether the normative pyrite is overestimated or not does not make any significant difference in the chemical composition of the sulphide fraction.

In this study, when referring to the sulphide fraction, the expression tenor is used, which means the metal content in the sulphide fraction. In tables and figures, the postfix <u>SF</u> is used (e.g. Ni SF%). Units are weight-based: percentages (SF %), grams per tonne (SF ppm) or grams per thousand tonnes (SF_ppb) if not otherwise stated. The sulphide content of the samples in this study is the sum of normative sulphide minerals in percentages. Therefore, weight the term normative sulphide content is used in the text, but in the figures the term Sulphides% is used without a normative prefix. If the amount of normative sulphide content exceeds 0.3%, then the cumulate is interpreted to have crystallised from sulphide-saturated magma, and the sulphide is a cumulus phase (chapter 3.2.2). The term with cumulus sulphides is also used for such a cumulate.

Table 9. Calculation of the sulphide fraction and normative sulphide minerals.

- (1) Weight percentages of chalcopyrite, pentlandite, cobalt pentlandite, sphalerite, galena, molybdenite and arsenopyrite are calculated as given below in the Equation column. Content of elements in equations are weight percentages in the sample.
- (2) Residual sulphur content is calculated. If that is negative, then all sulphides except pyrrhotite are set to zero, and pyrrhotite is calculated according to step 4.
- (3) If Fe analysis is carried out by the bromine-methanol method, then the amounts of pyrite and pyrrhotite are solved as follows: writing in matrix format the mass balance: $\begin{bmatrix} 36.48 & 53.45 \\ 63.52 & 0.07 \times 46.55 \end{bmatrix} \bullet \begin{bmatrix} Po \\ Py \end{bmatrix} = \begin{bmatrix} S \\ Fe \end{bmatrix}$, where S and Fe are residual

sulphur and iron contents after removing S and Fe bond in previously calculated sulphides. Po and Py are solved by non-negative least square method.

- (4) If Fe bromine-methanol analysis is not available, or the only Fe sulphide is pyrrhotite, then pyrite is set to zero and the pyrrhotite is calculated according to the equation: Po=100*S/36.48.
- (5) Trace elements in sulphides: Os, Ir, Ru, Rh Pt, Pd, Au, Re, Ag, Cd, Sn, Sb, Bi, Se, Te and Hg are added to the previously calculated sulphides.

(6) Sum of minerals and trace elements is the normative sulphide content (the word normative may be left out)

(7) Minerals and trace elements are recalculated to 100%

(8) Normalisation gives the trace element content in the sulphide fraction directly. The Cu, Ni, Co, Zn, Pb, Mo, and As content of the sulphide fraction is back calculated from the normative minerals. E.g. The Ni tenor: Ni_SF%=Pn_SF%*36.16/100. The iron and sulphur content are calculated by totalling the sulphur and iron content bound in each normative mineral.

Mineral	Symbol	Formula used	Element	wt.%	Fe wt.%	S wt.%	Equation
Chalcopyrite	Ccp	CuFeS ₂	Cu=	34.63	30.43	34.94	Ccp=100*Cu/34.63
Pentlandite	Pn	Ni _{4.76} Fe _{4.24} S ₈	Ni=	36.16	30.64	33.20	Pn=100*Ni/36.16
Cobalt pentlandite	Cpn	Co ₉ S ₈	Co=	67.40	0.00	52.94	Cpn=100*Co/67.40
Sphalerite	Sp	ZnS	Zn=	67.10	0.00	32.90	Sp=100*Zn/67.10
Galena	Ga	PbS	Pb=	86.60	0.00	13.40	Ga=100*ga/86.60
Molybdenite	Mb	MoS_2	Mo=	59.94	0.00	40.06	Mb=100*Mo/59.94
Arsenopyrite	Ару	FeAsS	As=	46.01	34.30	19.69	Apy=100*As/46.01
Pyrrhotite	Ро	FeS			63.52	36.48	(3) or (4)
Pyrite	Ру	FeS ₂			46.55	53.45	(3) or (4)



Figure 16. a) Normative pyrite content of the sulphide fraction, versus normative sulphide content and b) normative pyrrhotite content of the sulphide fraction versus normative pyrite content of the sulphide fraction. The normative pyrite derives most probably from the composition of normative pyrrhotite, which is FeS. The average ratio of normative pyrite and pyrrhotite implies that the pyrrhotite has the composition of $Fe_{0.903}S$ as an average.

4.5.2 Nickel and cobalt numbers (Ni#, Co#)

The Ni# and Co# are here calculated mainly from the AAS assays after bromine-methanol dissolution (BM+AAS, see above), and this is indicated by the postfix BM, thus Co#_BM and Ni#_BM. The detection limit of base metals by BM+AAS is 1 ppm and the coefficient of variation is 4% in concentrations above 10 ppm. Cobalt is the limiting factor in the accuracy of the calculations. In order to get a 2σ confidence level for Co# and Ni# <1, the sulphide content of the sample should be ≥ 0.3 wt.%, which is used as the limit in the study of the Co# and Ni#. In samples with >0.3% normative sulphides, the cobalt content is below the required 10 ppm in only 30 of 1530 samples.

In cases where a BM+AAS assay was not available, XRF analyses were used in calculating the Co# and Ni#. This is indicated by the postfix XRF, Co# XRF and Ni# XRF, except in part III (testing), where all the analyses were whole-rock assays and the postfix was left out. Determined form XRF vs. BM regression, the average nonsulphidic Ni content of the case study intrusions is 560 ppm and that of Co is 54 ppm. The Ni# XRF is on average 13 units higher than the Ni# BM in samples with 0.3-1.0 % normative sulphides, and the difference decreases as the sulphide content increases. The Co# XRF is on average 2 units higher than the Co# BM, and also for the Co#, the difference decreases with an increasing sulphide content. In samples with 0.3-1.0% normative sulphides, the standard deviation of the difference with these two techniques, BM and XRF, is 12 for the Ni# and 9 for the Co#, both decreasing as the sulphide content decreases (Figure 17).

4.5.3 Volatile-free (VF) and volatile- and sulphide-free (VSF) compositions

The calculation of volatile-free (anhydrous) composition is a common practice in petrological studies of mafic-ultramafic rocks and is a simple recalculation of selected elements to 100%. The



Figure 17. Difference between the Co# calculated from the whole-rock assays by XRF method (Co#_XRF) and that of calculated from the bromine-methanol + AAS analysis vs. normative sulphide content. The best fit curve close to y=0 shows that Co# is not sensitive to analysis method and even with whole-rock analyses reliable estimate can be attained. Diagonal 18 confidence lines show that for Co# calculated from the XRF analysis sensitivity in the important range with 0.3-1% normative sulphides is \pm 8 units.

main problem is the distribution of total iron between sulphides and the divalent and trivalent states in the rock, forming silicates and oxides. Iron incorporated in sulphides can be solved as described above in chapter 4.5.1. The proportion of ferric iron in mafic and ultramafic cumulates is normally low. This only has to be taken into account when chromite, magnetite or ilmenite are present as a cumulus mineral. In this study all non-sulphidic iron was calculated as total FeO in both volatile and volatile- and sulphide-free calculations.

Volatile- and sulphide-free composition (*VSF*) is an anhydrous chemical composition of the rock where the sulphides have been removed. When the composition of sulphide fraction has been calculated and the portion of base metals in sulphides is known, the calculation of volatileand sulphide-free composition is a simple recalculation of selected elements to 100%. If the composition of the sulphide fraction was determined from the bromine-methanol leach, the recalculation is reliable even for samples rich in sulphides.

The volatile- and sulphide-free composition (*VSF*) introduced in this study is very useful for Ni-Cu sulphide-bearing samples: it can be applied to compare the host rocks of sulphide-rich samples with ordinary cumulates and country rocks. In this study for the major elements the terms volatile- and sulphide-free composition are used. This is indicated with an $_n$ postfix (e.g. MgO_n) for clarity. Volatile- and sulphide-free contents are always in weight percentages.

4.5.4 Normative mineral composition

CIPW normative mineral composition provides in most cases a relatively reliable estimate on the (modal) mineral compositions of mafic-ultramafic igneous rocks. However, when the magma has been hydrous, CIPW norm may differ notably from the mode. When the sample is rich in phlogopite, then the CIPW norm is quite misleading. K is allocated in orthoclase, which is seldom present at all in mafic cumulates. The result is that the magnesium and iron in phlogopite are allocated in ferromagnesian silicates. olivine. orthopyroxene and clinopyroxene. Commonly in mafic and

ultramafic rocks, the CIPW norm overestimates the olivine content.

A novel calculation routine called B-norm was developed to make the estimations on mineral composition more reliable. The B-norm differs from the CIPW norm by containing phlogopite, and estimating uniquely the Mg/(Mg+Fe) ratio of mafic silicates. The calculation routine is described in Table 10. Equations to calculate the Mg# of the mafic silicates were derived from the mutual correlations of electron microprobe analyses of different minerals done for this study as shown in Figure 18. Figure 19 illustrates the advantages of B-norm compared to CIPW norm.

In this study, mineral contents refer to the checked volatile- and sulphide-free B-normative composition. This means that the normative mineral contents were checked microscopically in polished sections. Because the B-norm was calculated from the volatile- and sulphide-free composition, sulphides are excluded and mineral percentages are therefore normalised non-sulphide mineral contents in weight percentages. This practice was used to bring out the non-sulphide mineral composition of ore-hosting cumulates and to make them comparable with barren cumulates.

Table 10. Calculation of the B-norm:

1. The weight percentages of the various oxides are first computed into molecular numbers.

5a. Fe_2O_3 is allotted to magnetite (Mag).

- 6. Cr₂O₃ is allotted to chromite (Chr).
- 7. The rest of total Fe is assumed to be divalent, FeO, and it is combined with MgO, which is called FM.
- 8. K₂O is calculated as phlogopite (Phl).
- 9. Na₂O is calculated as albite (Ab).
- 10. Al_2O_3 is calculated as anorthite (An).
- 11. The rest of CaO is calculated to clinopyroxene (Cpx)
- 12. FM/ SiO₂ ratio is calculated
 - a) if 1<FM/ SiO₂<=2 then olivine (Ol) and orthopyroxene (Opx) are formed
 - b) if $0 \le FM/SiO_2 \le 1$ the orthopyroxene and quartz (Qtz) are formed
- $\begin{array}{c} 13. \ Mg\# \ of \ olivine, \ orthopyroxene, \ clinopyroxene \ and \ phlogopite \ is \ calculated \ according \ to \ following \ equations \ (Figure \ 20): \\ Mg\#(Opx)=0.157*Mg\#(Ol)+46.2 \qquad Mg\#(Cpx)=0.245*Mg\#(Ol)x+75.6 \qquad Mg\#(Phl)=0.850*Mg\#(Ol)+21.0. \end{array}$

^{2.} P2O5 is calculated as apatite (Apa).

^{3.} ZrO₂ is calculated as zircon (Zir).

^{4.} TiO₂ is calculated as ilmenite (Ilm).

b. If ferric iron is unknown, the amount of magnetite may be estimated from the amount of ilmenite, for example in Alter do Chão the ilmenite to magnetite ratio is 1:2.2

44 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 18. The Mg# (100*Mg/(Mg+Fe) in cation proportions) of <u>a</u>) orthopyroxene, <u>b</u>) clinopyroxene, <u>c</u>) amphibole and <u>d</u>) phlogopite plotted against forsterite content of olivine. These were all microprobe analyses. Lines were drawn by fitting by least the square sum method linear equation through the points. Fit equations are given in Table 10.

4.5.5 Chemical compositions of minerals

By mass balance, the concentration of an element E in a multi-phase mineral assemblage can be expressed as the sum of the products of the molar proportions X (as mass fractions of 1) times the concentrations W, of the element E, in a mineral phase Ma (Bedard 1994). The weight fraction of element E in sample is

$$W_{E,T} = \sum_{a=1}^{n} W_{E,Ma} * X_{Ma}$$
 (Equation 12),

where $W_{E,Ma}$ is the weight fraction of element *E* in mineral *Ma* and X_{Ma} is the weight fraction of mineral Ma in a sample. When the bulk composition ($W_{E,T}$) and weight fractions of minerals (X_{Ma}) are known, one can estimate weigh fraction of element in mineral $W_{E,Ma}$ by aplying the elemental partition coefficients between the minerals. The partition coefficients used in calculating the normative nickel content of minerals are given in Figure 20. Figure 19c shows the correlation between the analysed nickel content of olivine (determined by electron microprobe using trace conditions, chapter 4.3) and the calculated nickel content of the olivine (calculated from whole-rock composition and Bnormative olivine using Equation 7). R squared of the fit, >0.8, confirms that the nickel content of olivine can be calculated reliably enough from the whole-rock analyses.



c) Calculated Ni of olivine, ppm



Though the calculated forsterite and especially Ni content of normative olivine seems to give reliable estimate of true olivine, in the case studies in part II analysed compositions of mafic silicates are used almost exclusively. When normative compositions are used, it is clearly stated, e.g. *Ni content of normative olivine*. The purpose of the technique developed and presented above is to utilise it in cases where microprobe analyses are not available and the composition of the mafic silicates turns out to be essential parameters evaluating the fertility of the Ni exploration target (part III).





Figure 19. <u>a)</u> In the CIPW norm the calculation of orthoclase from the K_2O_n instead of phlogopite results in an excess of magnesium and iron, which is used to build up olivine, which amount is overestimated. In the B norm such a bias does not exist.

b) Though the B normative forsterite content of olivine is closer to the analysed one than in the CIPW norm, it is still too far away to be utilised reliably in nickel exploration instead of olivine analyses.

c) Correlation between the analysed nickel content of olivine (analyses by electron microprobe using trace element procedure) and calculated nickel content of normative olivine. R squared of the fit is 0.814. Samples from the case study intrusions.

46 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 20. Comparison of analysed nickel contents of olivine (on the x-axis) with <u>a)</u> calculated Ni tenors (fit equations: a) y=0.00616*x, $R^2=0.568$), <u>b)</u> analysed Ni content of orthopyroxene (y=0.196*x, $R^2=0.851$), <u>c)</u> analysed Ni content of clinopyroxene (y=0.131*x, $R^2=0.793$), and <u>d)</u> analysed Ni content of amphibole (y=0.298*x, $R^2=0.882$).

4.5.6 Normative cumulus name of the rock

To give the proper cumulus name for an igneous rocks is often time-consuming. Thin and polished sections of representative samples have to be studied. However, it was found that B-normative compositions are well in harmony with the actual primary igneous mineralogy. Consequently, a cumulus naming procedure was developed on the basis of the B-norm. If the CIPW norm is used instead, an overestimation of olivine (see above) has to be taken into account.

A comparison of the B-norm with the cumulus name defined by microscopy names made it possible to determine the threshold abundances above which minerals belong to a cumulus phase. For normative orthopyroxene, clinopyroxene, and plagioclase it was found to be roughly 25% and for normative olivine 10% (Table 11). The sum of the normative cumulus minerals identified in this way is higher than 50% in cumulates, but less than 50% in non-cumulate rocks such as volcanites. these observations, From the

A cumulus name consists of four parts; the naming rules in each part are as follows:										
1 Cumulus minerals	2 Cumulus type	3 Cumulus/rock	4 Intercumulus minerals							
		index								
Listed in the order of abundance using the following abbreviations. The normative abundance must be above the given boundary. o=olivine (>10%) b=orthopyroxene (>25%) a=clinopyroxene (>25%) p=plagioclase (>25%) m=magnetite (>10%) c=chromite (>0.6%) t=apatite(>1%)	If the rock is a cumulate, one of the following symbols is used to describe the amount of cumulus minerals. A=adcumulate (cumulus minerals>93%) M=mesocumulate (cumulus minerals 75-93%) O=orthocumulate (cumulus minerals 50-75%)	To distinguish if a rock is cumulate or non-cumulate: (cumulus minerals >50%) R=non-cumulate rock (cumulus minerals <50%)	Listed in the order of abundance using the following abbreviations. The normative abundance must be between the given boundaries. b=orthopyroxene (10-25%) a=clinopyroxene (10-25%) p=plagioclase (10-25%)							
\$=suipnides (>0.3%)		·								

Table 11. Automated cumulus naming procedure

e.g. oMCa=olivine mesocumulate with clinopyroxene as intercumulus mineral; bRpa=non-cumulate rock where the main phase is orthopyroxene and the other significant phases are, in the order of abundance, plagioclase and clinopyroxene

automated cumulus naming procedure was developed. Table 11 describes the default rules.

In this study the cumulus names were created from the B-norm, which was calculated from the volatile- and sulphide-free composition. This was done to bring out the name and nature of the cumulate hosting the sulphides along the same lines with barren cumulates. If sulphides occur as cumulus phase, decided from the normative sulphide content, it is normally added in the cumulus name in the text, i.e. olivine-sulphide cumulate. In places, where the nature of the hosting cumulate is stressed, the *sulphide* is left out from the name, e.g. "*ore is hosted by olivine cumulate*".

4.6 Subdivision of intrusions

Each intrusion was subdivided into different parts for purposes of description and genetic analysis (Irvine 1982, Zientek et al. 1985). Subdivisions of the intrusions intend to be as detailed as possible, so that magmatic modelling could be done comprehensively. Figure 21 describes the subdivision of the intrusion. The terms are defined below:

- **Complex:** A major layered intrusive complex; can contain several intrusions (e.g. Bushveld complex, Stormi is a complex consisting of several ultramafic intrusions).
- **Intrusion:** Igneous rocks produced in subsurface condition by a single magmatic system.
- **Block:** A separate part of an intrusion, in most cases it was separated by tectonic displacement.
- **Series:** Major stratigraphic successions of cumulates that can be a part of intrusion or block.



Figure 21. Nomenclature followed in this study for subdivision of intrusion and identification of distinctive parts or combination of parts in intrusion. Boxed hierarchy levels are compulsory, non-boxed may appear.

- **Zone:** First-rank stratigraphic subdivision of series, mappable part of a series.
- **Subzone:** Second-rank stratigraphic subdivision of series, part of a zone. Mostly non-mappable. Identified by chemistry and mineralogy.
- **Group:** Prominent combination of several similar units.
- **Unit:** Compositionally distinctive features that can be singled out and named or numbered for specific reference. They are not necessarily part of anything except intrusion.

Member: An outstanding single unit.

- The following specific terms are used strictly as defined below:
- **Rhythmic unit** (Irvine 1982): a succession of layer types that is repeated stratigraphically in a regular way.

Cyclic unit (Irvine 1982): a rhythmic unit in which the cumulus-mineral sequence can be identified as the fractional crystallization order of the magma.

In subdivision, descriptive and common rock names were used for zones as given in Table 12. Four of the intrusions (Laukunkangas, Alter do Chão, Bruvann, Porrasniemi) display a clearly layered structure and make it possible to define the original bottom and top of the intrusion. In these cases the stratigraphic column has been built up and presented against the stratigraphic height. In cases where the bottom and top of an intrusion cannot be identified, a reference profile is established and the rock sequence is presented against the profile distance (i.e. distance from the reference point along the reference profile).

Table 12. Summary of the zones (X) and subzones (s) established in the ca	se study intrusions.
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Intrusion	Dunite	Peridotite	Ultramafic	Pyroxenite	Mafic	Gabbro zone	Norite
	zone	zone	zone	zone	zone		zone
Alter do Chão			Х		Х	Х	
Bruvann		Х				Х	Х
Ekojoki	Х	Х					
Laukunkangas		Х					Х
Porrasniemi		Х		Х		Х	
Posionlahti	Х			S			
Rausenkulma		Х		Х		Х	
Rörmyrberget*							
Stormi	Х	S		S			

*Rörmyrberget was divided into units and members (chapter 9.3).

PART II: CASE STUDIES

5 INTRODUCTION TO THE CASE STUDIES

5.1 Targets

Nine intrusions from four countries and different geological environments were selected for case studies. The following criteria were applied: 1) intrusions must be well studied because this study aims to develop nickel exploration methods and tools rather than solve petrological problems, 2) the intrusions should cover various geological environments, and 3) fertile and barren intrusions should be included.

On the basis of economic significance the case study intrusions were divided into three groups:

- 1. <u>Fertile intrusions hosting mined, economic</u> <u>Ni-Cu deposits</u>: Bruvann, Laukunkangas and Stormi.
- 2. <u>Subeconomic intrusions hosting Ni-Cu</u> <u>deposits which have not been mined</u>: Ekojoki, Rausenkulma and Rörmyrberget.
- 3. <u>Barren intrusions</u>: Posionlahti, Porrasniemi and Alter do Chão.

Intrusion,	Code	Country/Area	Intrusion	Age	Ore reso	urces		
deposit		-	type	Ma	Status	Mt	Ni wt.%	Cu wt.%
Stormi	STO	FIN/Vammala	SMUI	1890	F	7.6	0.68	0.42
Laukunkangas	LAU	FIN/Enonkoski	SMUI	1880 ± 3	F	6.7	0.78	0.22
Bruvann	BRU	NOR/Ballangen	CAL	437±1/2	F	6.8	0.54	0.10
Rörmyrberget	ROR	SWE/Vindeln	SMUI		S	4.0	0.60	0.06
Ekojoki	EKO	FIN/Vammala	SMUI		S	1.2	0.46	0.41
Rausenkulma	RAU	FIN/Kokemäki	SMUI		S	0.04	0.68	0.95
Alter do Chão	ALT	POR/Badajoz	HER		В	0.00	0.32	0.002
Posionlahti	POS	FIN/Vammala	SMUI		В	0.00	0.26	0.14
Porrasniemi	POR	FIN/Lammi	SMUI	1879±3	В	0.00	0.21	0.12

Table 13. Studied intrusions.

Intrusion type: SMUI=Svecofennian mafic-ultramafic intrusions (1.8-1.9 Ga), CAL=Intrusions of Caledonian orogen, HER=Pre- to early hercynian intrusions in Spain and Portugal. Ore resources; Status: F=fertile (mined), S=subeconomic, B=barren (maximum nickel and copper grades are given). Data from Puustinen at al. 1995, and Outokumpu internal reports. Rörmyrberget data from Nilsson (1985), cut-off 0.4 wt.% (raising cut-off to 0.8 wt.% gives 0.66 Mtn 1.1 wt.% Ni and 0.08 wt.% Cu).

The code names, ages and ore resources of the case study intrusions are given in Table 13, and their locations are shown in Figure 15. According to lithologies the intrusions were divided into two ultramafic intrusions types: 1) and 2) differentiated mainly mafic intrusions. Ultramafic intrusions consist almost entirely of ultramafic cumulates. Layering is not a prominent feature, but different units can be recognized on the basis of geochemistry and mineralogy. Stormi, Ekojoki, Posionlahti, Rausenkulma and Rörmyrberget belong to this type.

Differentiated, mainly mafic intrusions include Bruvann, Laukunkangas, Porrasniemi and Alter do Chão. The intrusions consist of series of cumulates ranging from olivine cumulates to gabbroic and quartz-dioritic rocks with mafic rocks prevailing. Layering is a prominent feature and rhythmic layering can be recognized in outcrops and drill holes. Small intrusions (Laukunkangas and Porrasniemi) do not contain cyclic units, but in Bruvann several tens of cyclic units can be recognised. In Alter do Chão several separate cumulate series can be identified.

All the studied intrusions are related to orogenic activity; they are deformed, often contain cross-cutting igneous rock types and display metamorphic features and thus fulfil the criteria of orogenic intrusions accoriding to Naldrett (1989). Magmatic sulphide deposits in orogenic intrusions are sulphide dominant, in contrast to PGE-dominant deposits in intraplatelayered intrusions. Their parental magmas have been basaltic to high-Mg basaltic. Ore deposits in these intrusions have been small and of a low grade.

5.2 Svecofennian mafic-ultramafic intrusions

Most of the case study targets (Stormi, Posionlahti, Ekojoki, Rausenkulma, Porrasniemi, and Laukunkangas) belong to the Svecofennian mafic-ultramafic intrusions (e.g. Haapala 1969, Papunen and Vorma 1985; Gaál 1985; Papunen et al. 1979; Mäkinen 1987; Papunen 1996, 2003; Peltonen 2005), which have hosted the most significant mined Ni deposits of Fennoscandia. Twelve mines were operated in Finland by Outokumpu Oy after the Second World War, with a total production of ca. 46 Mt averaging 0.63 wt.% Ni and 0.24 wt.% Cu (Puustinen et al. 1995). The four biggest deposits are Hitura (started in 1970 and so far 13.5 Mt ore at 0.60 wt.% Ni and 0.22 wt.% Cu has been treated, data from Isomäki 2005), Kotalahti (1957-1987, 12.3 Mt, 0.72 wt.% Ni and 0.27 wt.% Cu), Vammala (1973-1995, 7.4 Mt, 0.69 wt.% Ni and 0.42 wt.% Cu) and Laukunkangas (Enonkoski mine, 1985-1994, 6.7 Mt, 0.76 wt.% Ni and 0.22 wt.% Cu).

Proterozoic (1800-1900 Ma) Svecofennian mafic-ultramafic orogenic intrusions occur mainly in Svecofennian migmatized metaturbidites in Finland and Sweden. The Svecofennian supracrustal domain is mainly composed of 1.9-2.0 Ga marine greywackes, island arc volcanic rocks and the 1.89-1.86 Ga intersecting granitoids them. Geological. geochemical and isotope-geochemical studies suggest that the Svecofennian orogeny is composed of at least two island arc systems and of their collisions and extensions during various stages of evolution (Kilpeläinen 1998; Korsman et al. 1988; Vaasjoki and Sakko 1988; Kähkönen 1989; Nironen 1989a, 1989b, 1997; Kähkönen et al. 1994; Lahtinen 1994; Korja 1995; Lahtinen and Huhma 1997).

Peltonen (2005) divided the intrusions in four main groups according to geotectonic domain: I: intrusions of the arc complex of western Finland, II: synvolcanic intrusions of the arc complex of southern Finland, III: Ti-Fe-P gabbros of the central Finland granitoid complex. Ni-Cu sulphide occurrences are found in group I, which is further divided in two subgroups, Ia: intrusions close to the Archean craton margin and Ib: intrusions of the Tampere and Pirkanmaa belts.

Nickel deposits related to the Svecofennian intrusions of groups Ia and Ib are almost exclusively confined to narrow relatively welldefined zones, which are characterised by high metamorphic grade (amphibolite facies), schollen and schlieren migmatites, sulphidic-graphitic metasediments, a large number of maficultramafic intrusions, and high regional gravity. The "nickel belts" were originally defined with petrochemistry and mineral chemistry of mafic silicates derived from mafic-ultramafic intrusions by Häkli (1971).

Two different intrusion types can be distinguished: 1) weakly differentiated <u>ultramafic</u> <u>intrusions</u> consisting almost entirely of olivine cumulates (also called Vammala type intrusions by Mäkinen 1987), and 2) differentiated mainly

<u>mafic intrusions</u> consisting of olivine cumulates, pyroxene cumulates and plagioclase-bearing cumulates (also called Kotalahti type intrusions, Mäkinen 1987).

Ultramafic intrusions are small (100-1000 m in diameter) boudinaged lenses or pipes enveloped by polydeformed paragneisses. They have been reinterpreted as remnants of synorogenic feeder dykes, sills and magma chambers that crystallised at mid-crustal levels of Svecofennian arc terrain.

Mafic intrusions are commonly bigger; in a surface section usually some km long and some hundreds meters wide. Magmatic layering is locally visible and the bodies may have a layered structure, which, however, may look relatively complex due to multiple deformation history. Olivine cumulates usually represent less than 10% of the total volume of the intrusion. Both ortho- and clinopyroxenes can be present and the whole spectrum from orthopyroxene-rich to clinopyroxene-rich cumulates is encountered in a single body.

Nickel deposits are found in both types. The nickel tenor is higher in type one (ca. 6-10 % vs. 4-8 % Ni_SF). The Ni/Cu ratio is typical for gabbroic deposits, ranging from 1.5 to 4 (Ni#=60-80, Naldrett 1989). Sulphide mineral assemblage is pyrrhotite-pentlandite-chalcopyrite and PGE tenors are low. Of the major deposits, Hitura and Stormi belong to type one and Laukunkangas and Kotalahti to type two.

In addition to the fundamental studies of Häkli (1963, 1970 and 1971) the works of Mäkinen (1987), Makkonen (1992, 1996) Peltonen (1995a, b, c and d) and Lamberg and Peltonen (1991) have dealt with the discrimination of barren and fertile Svecofennian intrusions. Mäkinen (1987) concluded that intrusions dominated by peridotites and norites are ore-potential, whereas pyroxenitic intrusions are barren. Makkonen (1992, 1996) found that Ni and Cu contents of olivine, orthopyroxene and chrome spinel studied together with their Mg# are potential indicators of sulphide deposits. According to Makkonen (1992, 1996) mineralized intrusions tend to have lower

Ni contents of olivine and higher abundances of elements associated with the contamination process. The works of Peltonen (1995a, b, c and d) indicated that contamination by sulphidebearing schists is the key process in the formation of Ni-Cu sulphide ores in the Vammala area. He suggested that mineralised intrusions could be distinguished from barren ones on the basis of moderately Ni-depleted olivine (Ni 500-1500 ppm at Fo=80%), Zn-rich chrome spinel (Lamberg and Peltonen 1991) and sulphides with high Cu/S and Se/S ratios.

6 BRUVANN

The Bruvann nickel-copper deposit is located some 20 km southwest of Narvik, Nordland, Norway (Figure 15). The deposit is hosted by Råna layered intrusion, which represents in this study a fertile, large, differentiated – mainly gabbroic – intrusion.

Norwegian geologists Foslie discovered the exposed Eastern orebody in 1912. Nickel exploration by Erzstudiengesellschaft (1940-1942), Norks Bergverk (1954-1960), Stavanger Stall with Geological Survey of Norway (1971-1974) and Leonhard Nilsen and Sönner (late 1980s) resulted in the opening of a mine in 1989 (Karppanen et al. 1999, Ekberg 1996). Mining continued till 2003 and a total of 7 Mt or ore at 0.54 wt.% Ni and 0.10 wt.% Cu was treated during that time.

The Råna intrusion was first described by Foslie (1921) and the general geology of the surrounding area by Gustavson (1921, 1974). The intensive nickel exploration by the Geological Survey of Norway from 1971 resulted in the description of the geology and ore deposit by Boyd and Mathiesen (1979), Boyd (1980a, 1980b) and Boyd and Nixon (1985). Barnes (1985, 1986 and 1989) and Boyd et al. (1987, 1988) studied the PGE potential of the intrusion.

Råna is an example of orogenic mafic intrusions, which occur in the Caledonides of Norway, Scotland and Finland. The intrusions were emplaced during the Caledonian orogeny at the closure of Iapetus Sea and the collision of the Laurentia and Baltica plates (Ihlen et al. 1997) ca. 400 Ma ago. The radiometric dating gave the age $437\pm\frac{1}{2}$ Ma for the Råna intrusion (Tucker et al. 1990) Several mafic-ultramatic intrusions of the Appalachian-Caledonian orogen are known to host low-grade Ni-Cu sulphide mineralisations (class IV.1 by Naldrett 1989 and class NC-5 by Naldrett 2004). Besides Bruvann, these include St. Stephen, Goodwin Lake, Mechanic and Portage Brook intrusions in New Brunswick, Canada (Paktunc 1987, 1988a, b, c and 1989) the Moxie, Katahdin, Union and Warren intrusions in Maine, USA (Rainville and Park 1976), and Huntly, Insch and Arthrath in Scotland (Fletcher 1988, Fletcher and Rice 1988, Plant et al. 1997, Fletcher et al. 1997, Gunn and Styles 2002). In Scandinavia, Bruvann can probably be correlated to other Caledonian mafic intrusive complexes like Halti-Ridnitsohkka (Sipilä 1992), Artfjellet (Senior and Otten 1985, Otten and Senior 1985), Fongen-Hyllingen (Habekost and Wilson 1989, Wilson 1985, Wilson et al. 1981), Honningsvåg (Robins et al. 1987), and possibly Vaddas (Stevens 1982) that were likewise emplaced at the peak of the Caledonian orogenic activity.

The Råna intrusion covers an area of 70 km^2 (Figure 22) and the interpreted shape is a cone plunging to the north-northeast with the thickest part and reaching a depth of 3 km. The Råna intrusion lies within the garnet-bearing gneiss with black schist intercalations. Noritic veins are encountered in gneiss some twenty meters below the contact of the intrusion.



Figure 22. Geological map of the Råna intrusion (modified after Boyd and Mathiesen 1975 and Karppanen et al. 1999).

6.1 Råna intrusion

6.1.1 Subdivision

Boyd and Nixon (1985) subdivided the Råna intrusion into four zones from the margin towards the centre: Contact norite, Ultramafic zone, Norite zone, and Quartz norite zone. This subdivision is guite similar to the St. Stephen intrusion, which consists of an ultramafic zone, Olivine-bearing mafic zone and the uppermost mafic zone (Paktunc 1987, 1989). Barnes (1985, 1986, 1989) renamed the Norite zone a Mafic zone, and in Tverfjell she identified several members and groups, and established a stratigraphic column of 15 megacyclic units. Each megacyclic unit includes a series of cumulates formed by fractional crystallization of silicates in the order: olivine-orthopyroxene-plagioclaseclinopyroxene. Barnes (1986) set the boundary between the Ultramafic and the Mafic zone the orthopyroxene cumulate between and plagioclase-orthopyroxene cumulate of unit five. The subdivision does not follow the common rules by Irvine (1982), and because it is not satisfactory for the present purpose the subdivision is re-established here.

Before the detailed description of the stratigraphic succession of the Råna intrusion and Bruvann, it must be stressed that the intrusion has been intensively deformed, faulted and veined. The fault directions and distances have been impossible to estimate in drill holes, and some of the veins may have been misidentified as

cumulate. Three different vein types have been identified: diabase, gabbro and pegmatoidal leuconorite. Numerous partly melted xenoliths and hybrid rocks obscure the original series of cumulates. Due to many difficulties a very simple hierarchy is established, and there are several features and samples, which do not perfectly fit in the stratigraphy. Several details have been omitted which evidently has resulted in an oversimplification of some locations.

The Råna intrusion is divided in this study into three blocks: Main block, Tverfjell block and Kvanåkertinden block (Figure 22 and Figure 23). In the Main block three different series are recognized: Basal series, Ultramafic series and Mafic series (Figures 23-26). Sampling was not extended to quartz norites (Quartz norite zone by Boyd et al. 1986), and this part of the intrusion is left out from the subdivision. All the identified series consist of cyclic units.

The Basal series comprises the Råna intrusion below the stratigraphic level where olivine appears as a volumetrically significant cumulus phase – similarly as in Stillwater – (Zientek et al. 1985). The basal series is heterogeneous and mainly consists of orthopyroxene-rich cumulates. Differentiation is broadly speaking reverse: upwards in the stratigraphy, the average MgO_n content of the units increase, mafic plagioclaseorthopyroxene members become thinner, and the first members of the units become more primitive and thicker.



Figure 24. Geological map of Bruvann (modified after Boyd and Mathiesen 1979 and Karppanen et al. 1999). Vertical drill holes sampled for this study are shown.

The Basal series is divided into three zones. the Norite sublayer zone (SNoZ), the Lower norite zone (LNoZ) and the Upper norite zone (UNoZ) (Figures . Noritic veins within the country rocks form the SNoZ. Veins are plagioclase-orthopyroxene cumulates. with MgO n ranging from 10 to 13%. The LNoZ consists of noritic rocks and olivine is mainly absent. The cyclic units of the lower Norize zone consist of thin olivine-plagioclase cumulates or thicker orthopyroxene cumulate members at the bottom and orthopyroxene-plagioclase cumulate members above it. A single unit can be rhythmically layered, which can be seen macroscopically due to change in modal percentages of orthopyroxene and plagioclase. The appearance of olivine as the cumulus mineral marks the beginning of the UNoZ. The olivine cumulate layers are thin and not present in all cyclic units of UNoZ. In the drill hole 235-160, the thickness of the Basal series is 100 meters.

The Ultramafic series generally overlies the Basal Series, but locally it is directly in contact with gneisses and most probably the contact is then tectonic. This Ultramafic series is dominated by ultramafic cumulates of the crystallisation series olivine-orthopyroxene-plagioclase (clinopyroxene). The olivine cumulates are voluminous and orthopyroxene-plagioclase cumulates are rare. The stratigraphic thickness of the Ultramafic series is 250 metres. It is composed of cyclic units, which commence with an olivine cumulate member and terminate with orthopyroxene or thin orthopyroxenean plagioclase cumulate member. In the drill hole 260-125, a total of eight cyclic units with an average thickness of 30 metres were identified. Due to the high amount of olivine and orthopyroxene, the ultramafic series is rich in MgO n as shown in Figure 27.







Figure 26. Stratigraphic interpretation of the section 2350E. Black bars indicate nickel content. Only disseminated ore type exists in this section.

On the basis of the presence of plagioclasebearing cumulates, the Ultramafic series is divided into three zones. Plagioclase-bearing cumulates are present in the cyclic units of the Lower peridotite zone (LPrdZ), but the Middle peridotite zone (MPrdZ) consists solely of ultramafic rocks. The appearance of plagioclase as a cumulus mineral marks the beginning of the Upper peridotite zone (UPrdZ) and the boundary is set to the bottom of the first cyclic unit, which contains plagioclase cumulate member. Subzones can be identified by their $Al_2O_3_n$ content in the whole-rock chemistry, as shown in Figure 27.

Pegmatoidal norites and granite veins crosscut the Ultramafic series and also mica gneiss inclusions are frequently encountered. Xenoliths are partly melted and in places hybrid rock types display gneissic texture. Besides the texture the hybrid rocks differ from the cumulates by their unique trace element chemistry (chapter 6.2).

A Mafic series overlies the Ultramafic series and it is marked by the appearance of clinopyroxene as a cumulus mineral in a cyclic unit as indicated by increase in the CaO_n content (Figure 27). Three of the sampled drill holes extend to the Mafic series and first 300 meters of the Mafic series is present in the longest one. The Mafic series is divided into two zones, the Lower gabbro zone (LGbZ) and Upper gabbro zone (UGbZ) on the basis of olivine cumulates, which are no longer met within the Upper gabbro zone. Cyclic units of the Mafic series are as an average less than 30 m thick. Units of the LGbZ commence with the olivine orthocumulate (oOC) or with olivine-plagioclase cumulate (opC). The next member is clinopyroxene-orthopyroxene or clinopyroxene-plagioclase cumulate, and the last one is plagioclase cumulate. In the UGbZ, the layering is identical, but the olivine cumulate member is missing. The mafic series is at least 350 metres thick. Quartz norite series is the uppermost series. It is not visible in the targets sampled and mapped for this study; therefore the reader is referred to Boyd and Mathiesen (1979).

6.1.2 Chemistry and mineralogy

Bruvann samples are generally fresh and nonaltered. The alteration of olivine to serpentine and magnetite is minimal, and hence it was difficult to apply geophysics to locate and delineate the olivine cumulates. The primary cumulus textures are well preserved. Alterations are met only in sheared samples, where the olivine is altered to carbonate and talc and orthopyroxene, clinopyroxene and plagioclase to secondary amphibole minerals. The sheared and altered samples were avoided in sampling and as the maximum total CO₂ content of cumulates is 1.5 wt.%, and the carbonate alteration is minimal.

The whole-rock composition of Bruvann cumulates reflect their mineralogy (Figure 27). MgO_n contents projecting the abundances of olivine are highest in the olivine mesocumulates of the Middle peridotite zone (37-41%). $Al_2O_3_n$ content parallels the amount of plagioclase and is approximately 20% $Al_2O_3_n$ in the Basal series, slips down to 2% in the Ultramafic series, and rises up again in the Mafic series, where it ranges from 5 to 20 wt.% $Al_2O_3_n$. The CaO_n content reflects the amounts of plagioclase and especially the clinopyroxene; CaO_n is above 10% when the clinopyroxene occurs as cumulus minerals. The cumulates of the Mafic series can be recognized in the CMA diagram from the bending

trend towards clinopyroxene and CaO apex (Figure 28). The average content of sulphides in the barren cumulates is 2.7 % (Figure 27). Sulphide mineralogy is discussed in chapter 6.2. Chalcophile elements, nickel, cobalt, copper and molybdenum follow the sulphides. The amount of normative intercumulus phlogopite is around 2 %. The concentration increases upwards in the Basal series, and a clear drop from 5% to 2% is recognized in the bottom parts of the Lower peridotite zone. The Cr_2O_3 n content is below 0.3 % in the Basal and Ultramafic series, but in the Mafic series the Cr_2O_3 n fluctuates from 0.4 to 1.0 % and attains high values in clinopyroxenerich cumulates and locally in olivine cumulates, too. Of the trace elements, SrO n follows normative plagioclase, Rb_2O n and BaO n normative phlogopite.

The Fo contents of the olivine range from 72.6 to 87.9% and correlate positively with the wholerock MgO n content and Mg# (Figures 29-30). The Fo content increases from 78.5% in plagioclase-olivine cumulates of the Lower norite zone, to 81% on the bottom of the Lower peridotite zone, and further from 84.5 to 87.5 in the Middle peridotite zone just below the disseminated ore. Within the disseminated ore the Fo content of olivine decreases from 85 to 82% and continues to drop in the Upper peridotite zone to 72.6%. A significant reversal to Fo₈₃ takes place between the Ultramafic and Mafic series. Upwards in the Mafic series the Fo content in the olivine cumulate members gradually decreases to 80.3%. The Ni content of olivine varies between 290 and 1340 ppm and follows roughly the Fo content when studied against stratigraphic heights (Figure 29), but in the xy-diagram the correlation is poor (Figure 30). The Ni content of olivine increases towards the disseminated ore in the Middle peridotite zone, decreases significantly above the ore to 600 ppm, and increases upwards to 1000 ppm in the upper part of the Mafic series.



Figure 27. Variation of chemical composition, sulphide and mineral contents and mineral ratios of Bruvann as a function of stratigraphic height in meters. Ores marked as solid dots (semimassive ore) and solid boxes (disseminated ore).



Figure 28. Samples of the Mafic series, i.e. Lower gabbro zone (LGbZ) and Upper gabbro zone (UGbZ) can be distinguished from the samples of the Basal series (SNoZ. LNoZ and UNoZ) and the Ultramafic series (LPrdZ, MPrdZ and UPrdZ) in CMA ternary diagram. Mafic series forms a path indicating the presence of clinopyroxene (Cpx), while the Basal series and Ultramafic series plot on a straight line from olivine and orthopyroxene (Ol and towards Onx) plagioclase (Pl).

The Mg# of orthopyroxene follows the Fo content of olivine [Mg#(Opx) = Mg#(Ol) * 0.466]+ 50.6; $R^2 = 0.842$] and ranges from 75 to 93%. Orthopyroxene contains as an average 2% a wollastonite component. The Ni content of orthopyroxene fluctuates according to the stratigraphic height parallel with the Ni content of olivine with the exception that the trend is mainly decreasing above the disseminated ore (Figures 29 and 30). The composition of clinopyroxene correlates with olivine, but less strongly than that of orthopyroxene. The Mg# of clinopyroxene varies from 83 to 93% and correlates positively with Al_2O_3 , which ranges from 1.2 to 4.1 %. The Cr_2O_3 content of clinopyroxene is between 0 and 1.6 wt.%, being highest in olivine cumulates, where the clinopyroxene occurs as an intercumulus mineral. V_2O_3 content in clinopyroxene is clearly higher than that in orthopyroxene, and is on the same level as in primary magmatic amphibole, 0.06-0.2 wt.% V_2O_3 .

Three types of amphiboles were observed: 1) intercumulus amphibole, 2) corona amphibole between olivine and plagioclase (mineral zoning

from olivine to orthopyroxene, amphibole and plagioclase) and 3) secondary amphibole after plagioclase and orthopyroxene. Intercumulus amphiboles display a higher TiO₂ (0.4-4.1 wt.%), and K₂O content (0.15-1.8 wt.%) than corona and secondary amphiboles.

Chromites of Bruvann are commonly homogeneous with Mg# ca. 35 and Cr# 45, but the chrome spinels in contact with olivine and orthopyroxene display weak zoning, and the grains against intercumulus minerals are zoned from brown chrome spinel cores to green spinel margins with Cr# < 15 and Mg# = 55-60. Also, homogeneous green spinels were found in some samples. Råna chromites have a distinctly lower $Mg/(Mg+Fe^{2+})$ ratio than those of layered intrusions, alpine-type peridotites, and Alaskantype complexes, but have similar compositions with chromites of Panton Sill, Australia (Hamlyn and Keys 1979), St. Stephen, New Brunswick, Canada (Paktunc 1987, 1989), Svecofennian intrusions of Finland (Figure 31 and Peltonen and Lamberg 1991, Peltonen 1995c), and arc-related settings (Snoke et al. 1981, Dick and Bullen 1984).



Figure 29. Chemical composition of minerals as a function of stratigraphic height. Sulphide compositions are shown in Ni# and Co# diagrams, where only samples with cumulus sulphides and not having plagioclase as the main cumulus mineral, according to normative criteria, are plotted.

60 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 30. Nickel versus 100*Mg/(Mg+Fe) <u>a)</u> of olivine and <u>b)</u> of orthopyroxene. All according to microprobe analyses. The reference lines indicate compositions of fractionated olivine in komatiitic and tholeiitic magmas according to Duke (1979). Lines in the orthopyroxene diagram are best fit lines of Bruvann (BRU), Laukunkangas (LAU) and Rörmyrberget (RÖR). <u>c)</u> Analysed forsterite content of olivine *vs.* MgO_n. The highest forsterite content analysed 87.9 is from the upper Peridotite zone. <u>d)</u> Comparison of calculated and analysed forsterite contents of olivine (R²=0.848, two outliers excluded).

Zn contents of Bruvann chromites range from 0.2 to 1.9 wt.% with highest values in the greenish rims of zoned grains (Figure 31b). The Zn contents of the cores and rims of unzoned grains is 1.2 wt.% at maximum. The Zn contents of chromite cores are not higher within the ore than the olivine cumulates beneath and above the ore. A correlation cannot be found between the zinc content of chromite and the normative sulphide content of the samples, nor between

Fe3⁺ or Ni and S content of the sample (Jinchuan by Barnes 1999a).

Minerals have re-equilibrated in subsolidus and metamorphic stages. This is proved by the Mg/Fe ratios of minerals, Ni to Fe ratios of silicates versus those of sulphides (chapter 11.1.2) and metamorphic textures. The Olivine corona textures in Bruvann are similar to the textures described in the Halti-Ridnitsohkka Caledonian igneous complex by Sipilä (1992).







Figure 31. Composition of chromite in the case study targets plotted on <u>a)</u> Cr#-Mg# projection of the spinel prism and <u>b)</u> Zn content versus Cr#. Fields in figure a are 1=Alpine type peridotites, 2 = S.E. Alaskan intrusions, 3 = Abyssal peridotites, <math>4 =Alpine-alpine type peridotites, 5 =boninites, 6 = layered intrusions, (Dick and Bullen 1984, Irvine 1977, Irvine 1967). Bruvann chromites with high zinc and low Cr# are the rims of zoned grains.

6.2 Nickel-copper ore

The Bruvann nickel-copper deposit is located in the Ultramafic series stratigraphically at 100-300 metres above the basal contact (Figure 27). The uppermost five meters of the Basal series are locally mineralised. A major subvertical fault zone divides the ore into two parts: Eastern and Western ore bodies (Ekberg 1996, Figure 25). The vertical distance between them varies between 130 m and 200 m, increasing towards north. Semimassive and disseminated ore types exist in two ore horizons (Figures 25-27).

<u>A Semimassive ore</u> is located lower in the stratigraphy, at the boundary between the Basal series and the Ultramafic series. The host rock is plagioclase-orhopyroxene cumulate or gabbroic-noritic hybrid rock. MgO n content is typically

around 10%. The normative sulphide content varies from 20 to 100 wt.%, being commonly about 30 wt.%. The base metal contents are slightly higher than in the disseminated ore: Ni =0.5-4 wt.%, Cu = 0.05-0.4 wt.% and Co = 0.04-0.25 wt.%. The semimassive ore is quite thin, commonly only a couple of meters, but locally up to 15 meters thick (Figure 25). The Ni tenor is clearly lower than in the disseminated ore: commonly 3 % and ranges from 2 to 5 %. The semimassive ore contains 0.5-5 wt.% graphite (Figures 32 and 33) and frequently anomalously high concentrations of V_2O_3 n, MnO n, Zn and Mo and locally also P_2O_5 *n* and Y (Figure 33a-e). Ni# varies widely from 67 to 95 and displays a positive correlation with Co# (Figure 34f).

62 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 32. The mode of occurrence of graphite in Bruvann. In disseminated and semimassive ore graphite (Gph) is intimately associated with sulphides (pyrrhotite Po, pentlandite Pn and chalcopyrite) occurring as inclusions and rimming them. <u>a-d</u>) Sample 9619387, 235-160/7727-773.0 m, ap\$C in the Upper gabbro zone, \$ (normative sulphide content) = 16.6%, Ni = 0.124 wt%. <u>e</u>) Sample 961387, 235-160/772.7-773.0 m, ap\$C, Upper gabbro zone, \$ = 13.6 %, Ni = 0.124 wt.%. <u>f</u>) Sample 9619421; 260-125/178.4-179.0 m, \$pbC, Upper norite zone, semimassive ore, \$ = 40.2 %, Ni = 1.1 wt.%.

<u>The disseminated ore</u> is hosted by the most primitive olivine cumulate of the Middle peridotite zone in the Ultramafic series. This cumulate unit is relatively thick, 50-250 m and contains the most Mg-rich olivine with a forsterite content ca. Fo₈₂. The MgO_n content is typically 37–41 %. Sulphides comprise less than 10 wt.% of the olivine mesocumulate host rock and the average Ni content of the ore is modest, 0.5 wt.%, the Cu is 0.15 wt.% and Co 0.02 wt.%. The Ni tenor ranges from 6 to 10 % being normally around 8 %. The Ni# is high and varies in a narrow range (75-84). The Co# is low, 2.5-7, and it varies independently from the Ni# (Figure



Figure 33. Bruvann. a) Olivine-sulphide cumulate of the disseminated ore. Sample 9619465, 270-135/211.7-212.1 m, oMC, MPrdZ, = 32.4 %, Ni = 1.63 wt.%. b) Mineralised orthopyroxene (Opx) – sulphide cumulate. Sample BH-534/12.20 m, bC, UNoZ-LPrdZ. c) Barren orthopyroxene (-sulphide) cumulate with poikilitic intercumulus plagioclase. Sample 9619360, b(C), LGbZ, = 0.57 %, Ni = 0.023 wt.%. d) Partly digested graphite schist inclusion in orthopyroxene-sulphide cumulate. Sulphides consist of pyrrhotite, pentlandite and chalcopyrite. Sample 9632719, Arnes, ab(C, = 3.2 %, Ni = 0.017 wt.%.

34f). The volatile- and sulphide-free host rock chemistry of the disseminated ore does not differ from the corresponding barren olivine cumulates, only the MnO_n content is slightly anomalous (Figure 34d).

Mineralogically, both ores are typical Ni-Cu sulphide ores with pyrrhotite, pentlandite and

chalcopyrite as the main sulphide minerals. Graphite and molybdenite are frequently met in massive sulphide samples. Ni-As-Co-S minerals (nickeline, maucherite, cobaltite-gersdorffite), molybdenite and Bi-tellurides occur as rare and small, disseminated crystals. A rare Re-mineral was identified in one sample.



Figure 34. Compositions of ore types (semimassive and disseminated ore) compared to those of cumulates and black schist. C (cross) = barren cumulate, BS (triangle) = black schist, D (box) = disseminated ore, SM (circle) = semimassive ore, GN=country rock, gneiss. Note that magnesium and vanadium content are presented as volatile- and sulphide-free contents (n) while the other elements as non-normalised original analyses results. Curves and lines are used as discrimination (Table 18).

Chemical composition of the sulphide fraction of selected samples is given in Table 14 and illustrated in a chondrite-normalised spidergram in Figure 35. Platinum-group element concentrations of the ore are low, less than 0.1 times of chondritic values for all the samples and elements. In four analyses, the highest total PGE content is recorded in the disseminated ore sample, 44.6 ppb Σ PGE. The PGE tenor is low in the ores, as well, 140-1680 ppb in disseminated ore and only 33 ppb in the semimassive ore (only one analysis). The highest concentrations in the sulphide fraction are recorded in sample from the Lower norite zone. The ratio of platinum-group elements favouring sulphide liquid (Os, Ir, Ru, Rh) to PGEs favouring monosulphide solution (Pt, Pd) drawn against the Ni# shown in Figure 35b do not indicate fractionation of the sulphide liquid.

G 1	0(10204	0(10215	0(1021(0(10225	0(10222	0(10250	0(102(1	0(10410
Sample	9619304	9619315	9619316	9619325	9619333	9619359	9619361	9619419
Drill hole	235-160	235-160	235-160	235-160	235-160	235-160	235-160	260-125
Depth, m	125.5	198.2	204.3	302.5	370.4	547.0	555.0	175.0
SubZone	LNoZ	UNoZ	MPrdZ	MPrdZ	UPrdZ	LGbZ	LGbZ	UNoZ
Oretype		D	D	D				SM
Cumulus name	poC	bC	oMC	oOC	oOC	oR	pC	
Sulphides, normative %	1.2	6.4	2.6	6.5	0.3	1.2	0.4	98.5
MgO n%	19.8	28.6	37.6	34.2	30.7	29.0	12.3	10.2
Ni (BM) wt.%	0.042	0.333	0.203	0.383	0.014	0.072	0.009	3.793
PGE total, ppb	46.1	15.8	44.6	9.0	0.0	8.1	0.1	31.9
Ni SF%	3.6	5.2	7.7	5.9	5.1	5.7	2.1	3.9
Co SF%	0.5	0.3	0.5	0.3	1.2	0.4	0.6	0.2
Ir SF ppb	11	17	46	3	0	10	0	4
Ru SF ppb	0	19	58	0	0	0	0	9
Rh SF ppb	12	9	23	5	0	14	14	1
Pt SF ppb	583	126	607	68	0	425	0	6
Pd SF ppb	3345	74	948	64	0	201	0	13
Cu SF%	1.0	1.5	2.3	1.2	1.2	2.2	0.8	0.4
Ni#	78.4	78.0	77.3	83.2	80.7	72.1	73.8	90.0
Co#	10.1	41	43	43	15.8	5.1	17.6	5.0

Table 14. Composition of sulphide fraction of selected samples.





Figure 35. <u>a)</u> Composition of the Bruvann sulphide fraction normalised to C1 chondrite. The analyses are given in Table 14. <u>b)</u> (Pt+Pd)/(Ru+Ir) versus Ni# (100*Ni/(Ni+Cu)) where the arrows indicate the evolution of a sulphide liquid (solid) and monosulphide solid solution (Mss, open) in the fractionation of Mss from the sulphide melt. Numbers refer to sample numbers Table 14).

6.3 **Genetic considerations**

6.3.1 Parental magma and crystallisation trends

The composition of the magma producing the cumulate sequence observed has changed significantly from the Basal series to the Mafic series. In the Basal series the cumulus sequence refers to the magma type, the crystallisation series of which is: olivine-plagioclase-orthopyroxene and olivine-orthopyroxene-plagioclase. Cumulus clinopyroxene is absent and olivine is missing in most of the rhythmic units. Olivine meso- and orthocumulates of Bruvann plotted in the olivine projection of the basalt tetrahedron in Figure 36 according to the guidelines of Irvine (1970 and 1979) illustrate the compositional change of the magma. However, this plot has to be studied warily, since the current intercumulus material may not anymore represent the magma composition due postcumulus and to metamorphic alteration processes like filter pressing and metasomatism. Moreover, in studied

Cpx moln X 3) UNoZ +5) MPrdZ 6) UPrdZ ∇ 7) LGbZ

intrusions the intercumulus material is enriched in subsequent cumulus mineral compared to the magma.

Stratigraphically. the lowermost olivine cumulates of the Upper norite zone plot in the plagioclase field of the olivine projection, and towards the Lower peridotite zone the composition of the silicate liquid gradually shifts to orthopyroxene field, as shown by an arrow in Figure 36. The changes can also be seen in CaO/Al₂O₃, which is around 0.5 in the Basal series but decreases to 0.44 in the Ultramafic series (Figure 37).

In the Ultramafic series, the magma composition remains in the orthopyroxene field of the olivine projection (Figure 36) producing cumulates according to the crystallization series olivine-orthopyroxene-plagioclase. The CaO/Al₂O₃ increases steadily from 0.4 in the Middle peridotite zone to 0.6 in the Upper peridotite zone, which equals the shift towards the orthopyroxene field shown by an arrow in Figure 36.

> Figure 36. Olivine mesoand orthocumulates, plotted on olivine projection of the basalt tetrahedron (plotting and lines according to Irvine 1970, 1979 and Irvine et al. 1983) and the compositional shift of the silicate liquid at the beginning of the Upper norite zone, Middle peridotite zone, Upper peridotite zone and Lower gabbro zone (arrows). In the Basal series olivine appears as cumulus mineral in the Upper norite zone. Towards the Ultramafic series melt changes SiO2-richer, as illustrated by shift to orthopyroxene field. In the Ultramafic series the crystallization sequence of the melt is olivine-orthopyroxene-plagioclase. In the Mafic series the melt composition shifts from the orthopyroxene field to a plagioclase field, producing gabbroic cumulates.





Figure 37. Variation of selected elements and indices in the stratigraphic column of Bruvann illustrating the evidence of linear and nonlinear shifts in the magma composition. <u>a)</u> CaO/Al₂O₃, <u>b)</u> calculated forsterite content of olivine, <u>c)</u> calculated nickel content of normative olivine, <u>d)</u> modified crystallisation index (von Gruenevaldt 1973).

In the Mafic series, the magma composition has changed to produce cumulate sequences with clinopyroxene as the cumulus mineral. As shown in Figure 36 the crystallisation series varies from olivine-plagioclase-clinopyroxene to an almost simultaneous appearance of plagioclase, orthopyroxene and clinopyroxene. Change in the magma composition is reflected in the increase of CaO/Al₂O₃ of the cumulates to 0.6-0.8 (Figure 37), and reversals in Mg# (Figure 27) and in compositions of olivine and clinopyroxene (Figure 29 and Figure 37). The Al₂O₃/TiO₂ value, which is not shown in the diagram, is in all olivine cumulates close to the mantle value 20.

For genetic discussion and numerical modelling, the magma composition was calculated for each series. In the Ultramafic series, the highest Fo-content of olivine is $Fo_{87.9}$ and with the trapped liquid shift (Barnes 1986) Fo_{88} was considered as a conservative estimate for the maximum Fo-content of the series with

1400 ppm nickel. Barnes (1986) reported a similar forsterite estimate in the Tverfjell block. The sequence of olivine cumulates with Fo_{88} is in equilibrium with liquid with 12.2 wt.% MgO and 9.7 wt.% FeO (Beattie et al. 1991, 1993). The content of the other elements were estimated using the regression analysis of olivine cumulates as described by Chai-Gang and Naldrett (1992) for the Jinchuan intrusion (Figure 38). The correlation of MgO n with Al_2O_3 n and CaO n is good ($\mathbb{R}^2 > 0.85$), moderate with SiO₂ n and SrO n $(0.85 < R^2 < 0.75)$, poor with V_2O_3 n and Na_2O n $(0.75 \le R^2 \le 0.60)$, and hardly or non-existing with the rest of the elements. For the elements showing no correlation with MgO n, the estimated concentrations are calculated from chemical compositions of minerals, literature data on parental magmas and observed ratios of elements in a similar way as Barnes (1986) calculated the melt composition of Tverfjell. The results are given in Table 15.

68 Geological Survey of Finland Bulletin 402 Pertti Lamberg

In the Mafic series the highest Fo-content of olivine is 84.6%, which was taken as an estimate for most of the magnesian olivine. The magma composition was estimated similarly as in the Ultramafic series keeping in mind that according to Figure 36 the magma composition lies close to the invariant plagioclase-clinopyroxene-orthopyroxene point. Although the correlations between MgO_n and other elements are better in the Mafic series than in the Ultramafic series, the estimate is not reliable, because the number of olivine cumulate samples is small (n = 5 Figure

38). The estimate of the Basal series is based on the most *Fo*-rich olivine ($Fo_{83.1}$), the regression of three olivines and interpreted location in the olivine projection of the basalt tetrahedron.

Estimated compositions of the parental magmas of different stratigraphic units are given in Table 15. Nickel, copper and cobalt contents are discussed in chapter 6.3.4. Although the compositions of magmas are estimates only, and can differ significantly from the actual melts, their mutual differences are significant and can be used in numerical modelling.



Figure 38. The composition of the magma in equilibrium with olivine ortho- and mesocumulates can be determined by regression analysis. The magnesium content of the melt was defined on the basis of olivine composition. $\underline{\mathbf{a}}-\underline{\mathbf{c}}$ Ultramafic series and $\underline{\mathbf{d}}$ mafic series.

Series	UmS	MaS	BaS (LGbZ)	BaS (UGbZ)
SiO ₂ %	51.9	49.3	49.2	53.31
TiO ₂ %	0.984	0.9	0.961	1.07
Al ₂ O ₃ %	14.82	13.46	14.4	16.2
Cr ₂ O ₃ %	0.17	0.188	0.2	0.183
FeOtot%	9.66	12.1	12.52	10.74
MnO%	0.163	0.17	0.174	0.163
MgO%	12.23	11.47	10.6	7.45
CaO%	7.44	9.62	9.22	8.1
Na ₂ O %	1.511	1.75	1.88	1.65
K ₂ O %	0.418	0.39	0.42	0.45
$P_2O_5\%$	0.076	0.067	0.072	0.083
Co ppm	47	38	29	57
Ni ppm	134	132	122	70
Cu ppm	22	32.4	29	19.6
Al ₂ O ₃ /TiO ₂	15.1	15.0	15.0	15.1
CaO/Al ₂ O ₃	0.50	0.71	0.64	0.50
Ni#	81.3	80.3	80.8	78.1
Co#	19.6	18.8	16.1	38.9
OBSERVED VALUES IN	CUMULATES			
Al ₂ O ₃ / TiO ₂	15	15	18	18
CaO/ Al ₂ O ₃	0.45	0.7	0.5	0.5
Max Fo% (analysed)	87.9	84.6	83.1	80.2
Ni of olivine, ppm	1330	1140	1141	991
Ni# of sulphides	75.3	81.2	81.8	79
Co# of sulphides	2.7	4.7	4.0	9.5
Crystallization order	Ol-Opx-Pl/Cpx	Ol-Cpx-Pl/Opx	Ol-Opx-Pl	Ol-Opx-Pl
Sulphur saturated	Yes	Yes	No	Yes
MODELLED COMPOSIT	TIONS			
Fo% of olivine	88	84.6	83.1	80.2
Ni of olivine, ppm	1400	1140	1140	990
Ni#	82	81.2	81.7	79
Co#	3	4.7	4	9.5

Table 15. Estimated compositions of the magmas in equilibrium with different stratigraphic units of the Bruvann sequence, % = wt.%.

6.3.2 Origin of graphite and sulphur

One of the most striking features of the sulphide-rich samples of Bruvann is the presence of graphite in various amounts in association with the sulphides. In some samples graphite laths or flakes occur concentrically in the sulphide 32). On the basis of droplets (Figure microscopical observations and sulphides vs. total carbon relationship a rough positive correlation between the graphite and sulphide exits abundances. Graphite can be found practically in all the samples of the semimassive ore, but it is also common in the disseminated ore (Figure 32).

Two alternative origins of graphite can be considered: (1) graphite is inherited from the surrounding host graphite schist and provides evidence of contamination from the host rock, or (2) graphite is magmatic and was crystallised early from the melt. In order to solve the problem, a set of samples were analysed for carbon isotopes (Table 16). Graphite schist exhibits a low δ^{13} C value of -21.5 % corresponding to the isotopic composition of mature organic matter (Ohmoto 1986). The δ^{13} C values of -14.0 and -14.8 of graphite from the Upper gabbro zone are close to the values previously reported for pyroxenites, eclogites and kimberlites (Pineau et al. 1987, Deines et al. 1987, Pearson et al. 1991, 1994) and mantle- derived graphitic carbon in mafic rocks (Pearson et al. 1994). The lower δ^{13} C values around -20 ‰ of the semimassive ore

samples may be the result either (1) of a contamination of the magma by the graphite schists, or (2) the ¹³C content of the dissolved magmatic carbon decreased in the Rayleigh distillation during CO₂ degassing (Pineau and Javov 1994). The following important observations are in favour of the contamination hypothesis: A) Small graphite schist xenoliths are encountered in the intrusion (Figure 32), B) The δ^{13} C value of graphite in cumulates and ore samples is inversely related to graphite concentration, which is the opposite of the trend expected from CO₂ degassing and related Rayleigh distillation (Figure 39a, Pineau and Javoy 1994). C) The ore sample richest in graphite (4.8 wt.%), exhibits a δ^{13} C value close to the δ^{13} C value of graphite in black schist (Figure 39a). D) Graphite contents display positive correlations with concentrations of MnO n, Mo, Zn and V_2O_3 n (Figure 34), which are abundant and characteristic elements of black schists. E) Graphite is present in hybrid noritic rocks with gneissic texture within the intrusion.

The close association of sulphides and graphite suggest their common origin. Sulphur isotopes and the sulphur to selenium ratio was studied to solve the source of sulphur. Sulphides from the graphite schists (Figure 39b, Table 16) display a low δ^{34} S value of -10.4‰, within the range commonly reported for sedimentary sulphides (Coleman 1977, Ohmoto 1986). Ore samples are within the range of mantle-derived sulphur (from -3 to +2 ‰. Ohmoto 1986). In graphite-bearing cumulates, the δ^{34} S values are lower (-4.7 and -6.0%) suggesting local contamination by sulphur originating from the graphite schists. The selenium to sulphur ratios do not give any information on the sulphur source, since the Se/S values of two black schist samples range from 136 to 340 $*10^{-6}$ while in the cumulate and ore

Table 16. Sulphur, carbon and oxygen isotope compositions of analysed samples from Bruvann and composition of some selected elements. SM = semimassive ore, D = disseminated ore; host rock definitions are cumulate abbreviations

Sample No	252	419	421	423	315	325	464	285	395	385	387
Zone		UNoZ	UNoZ	UNoZ	UNoZ	MPrdZ	MPrdZ	MPrdZ	LGbZ	UGbZ	UGbZ
Ore		SM	SM	SM	D	D	SM	SM			
Host rock	BS		pbC	boC	bC	oOC	oMC	bpC	oOC	pC	ApC
$\delta^{34}S$	-10.4	+0.6	-0.3	-2.8	-0.7	-0.1	+1.8	-1.6	+1.0	-4.7	-6.0
$\delta^{13}C$	-21.5		-20.4	-20.3				-19.8		-14.0	-14.8
$\delta^{18}O$					+8.4	+7.8	+7.7	+7.8	+7.7	+8.1	
εNd T	-6.4		-6.2		+0.1	+0.6					
(La/Sm)_N	2.4		3.4	2.8	1.3	1.7					
(La/Yb)_N	5.1		5.7	1.6	0.7	2.2					
Eu/Eu*	0.6		1.4	1.2	1.2	1.6					
Sulphides%	20.6	98.5	40.2	27.5	6.4	6.5	18.9	30.0	0.5	1.5	13.6
MgO_n%	6.2	10.2	11.1	19.5	28.6	34.3	41.2	9.6	33.7	9.6	12.1
$V_2O_3\%$	0.0943	0.0101	0.0441	0.119	0.0582	0.0248	0.0142	0.0571	0.0147	0.0439	0.0577
$V_2O_3_n\%$	0.1327	0.3567	0.0758	0.1761	0.0647	0.0277	0.0179	0.0853	0.0153	0.0451	0.0704
С%	10.8	0.1	1.6	4.8	0.1	0.5	0.1	1.8	0.4	0.7	2.4
Cu%	0.033	0.412	0.365	0.057	0.101	0.090	0.218	0.048	0.011	0.002	0.075
Ni%	0.033	3.600	1.120	0.977	0.443	0.552	0.810	0.809	0.082	0.010	0.124
Co%	0.007	0.219	0.071	0.060	0.024	0.031	0.054	0.064	0.012	0.009	0.033
Mo%	0.0035	0.0041	0.0008	0.0016	0.0000	0.0000	0.0000	0.0016	0.0000	0.0000	0.0006
Zn%	0.015	0.004	0.013	0.014	0.007	0.008	0.014	0.020	0.009	0.003	0.002
S%	7.27	36.55	14.61	10.10	2.41	2.42	6.94	11.00	0.18	0.55	4.97
Se ppm	9.9	25.0		8.4	3.4	3.3					

Samples (9619-: drill hole/depth): 252:235-120/29.1-29.4; 419:260-125/175.0-178.0; 421: 260-125/178.4-179.0; 423: 260-125/183.8-184; 315: 235-160/198.1-198.4; 325: 235-160/302.5-302.7; 464: 270-135/207.0-207.5; 285: 235-120/316.4-316.6; 395: 260-125/13.0-13.2; 385: 235-160/756.0-756.4; 387: 235-160/772.7-773

samples the corresponding values are between 70 and 220 *10⁻⁶. According to Eckstrand et al. (1989), the mantle Se/S values are between 250 and 350 *10⁻⁶, which would rather support the crustal origin of sulphur in Bruvann. Since δ^{34} S displays negative correlation with graphite content (Figure 39c), a part of sulphur in the massive ore could be of the black schist origin. In the disseminated ores, however, sulphur isotopes indicate that only a minor part of sulphur is derived from black schists and the major part is of mantle origin.

6.3.3 Contamination

Contamination of black schist and the related sulphide saturation of magma probably play major roles in the ore-forming process, and hence the identification of contaminated intrusion or a part of it could be a potential guide to screen favourable targets in nickel sulphide exploration. This hypothesis was tested in Bruvann with a geochemical study of stable and radiogenic isotopes (Sm/Nd, S, C and O isotopes), REE and black schist indicator trace elements. The results of isotope analyses are given in Table 16.



Figure 39. Stable isotope data. SM=semimassive ore type, D=disseminated ore type.
The $\varepsilon_{Nd}(T)$ calculated at the time of emplacement (437 Ma, Tucker et al. 1988) are close to zero for the barren and disseminated ore samples (-2.6 to +0.6) and correspond to chondritic values. For the semimassive ore sample, the value is lower (-6.2) and very close to the value obtained for the graphite schist. Values around zero in the disseminated samples could either reflect a chondritic mantle source for the complex, or contamination of a depleted mantle source with Lower Proterozoic crust.

 $\delta^{18}O$ values of Bruvann are homogeneous, around +8.0±0.3‰, independently of the normative sulphide content or silicate mineralogy of cumulates (Table 16). The high $\delta^{18}O$ values are anomalous for ultramafic rocks, which commonly display lower $\delta^{18}O$ values, ranging from +5.3 to +6.4 ‰ (Taylor 1966). High and homogeneous $\delta^{18}O$ values indicate a large-scale contamination and equilibration of silicate magma with crustal material.

Graphite schist is enriched in light rare earth elements (LREE) compared to heavy rare earth elements (HREE) (Figure 41). Abundances of LREE are hundred times the values of mantle, and the mantle normalised lanthanum to ytterbium ratio, $(La/Yb)_N$ – which commonly is used to describe the rations LREE to HREE - is 5.1. The fractional crystallization of olivine, orthopyroxene and clinopyroxene, which incorporate HREE > LREE, enrich the residual melt strongly in LREE and slightly weaker in HREE. Eu enters readily in plagioclase causing a positive Eu anomaly in the REE distribution pattern of plagioclase cumulates and negative in the residual liquid of plagioclase crystallisation. Besides a positive Eu anomaly, the presence of cumulus plagioclase will enrich the sample by LREE. In most of the cumulate and ore samples of Bruvann the [La/Yb]_N value is close to that of the mantle ($[La/Yb]_N \approx 1$) and Eu anomaly is missing or weak (Eu/Eu*<2, Figures 39 and 40). REE geochemistry of these samples gives evidence of a non-contaminated character. LREE enrichment in two plagioclase-bearing cumulates with positive europium anomalies is the result of plagioclase accumulation, and the cumulates are interpreted to be non-contaminated. Three samples show high [La/Yb]_N value (>3) without a positive europium anomaly (Eu/Eu*<1.5), and the



Figure 40 <u>a)</u> Magnitude of the europium anomaly Eu/Eu* vs. mantle normalised La-Yb ratio. High La/Yb values are due to cumulus plagioclase or crustal material. In the former case Eu/Eu* is high and in the latter case it is low as in the semimassive ore samples. Samples with high La-Yb ratio ((La/Yb)_N>3) without positive europium anomaly (Eu/Eu*<1.5) are interpreted to be contaminated with crustal material <u>b)</u> ε_{Nd} vs. mantle normalized ratio of La/Yb. Low ε_{Nd} with high La/Yb indicates the presence of crustal material.

LREE enrichment is interpreted to indicate the contamination by LREE-rich crustal material. Two of the contaminated samples are semimassive ores and one is an olivine cumulate member of the Lower gabbro zone. The other four ore samples (three disseminated and one semimassive) cannot be regarded contaminated on the basis of REE geochemistry.

The overall high normative sulphide content of

the Bruvann cumulates is an evidence of sulphur saturation caused by crustal contamination of the magma, as discussed in chapter 3.2.2. The average normative sulphide content of non-ore cumulate samples is 1.5 %, and 88 % of these samples contain more than 0.3 % sulphides (Figure 42). Surprisingly the average sulphide contents of the zones hosting the ore are lower than the other zones.



Figure 42. a) Normative sulphide content of rock types of Bruvann (left, BS=black schist, C=ordinary cumulates, D=disseminated ore, GN=gneiss, SM=semimassive ore) and b) box and whisker diagram (right) of statistics of normative sulphide content in ordinary cumulates in different subzones. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20.

Various indicators of the crustal contamination discussed above give contradictory information. Table 17 summarizes sample by sample the interpretations based on C isotopes, S isotopes, Sm-Nd isotopes, REE, and whole-rock chemistry (C, Mo, Zn, MnO n and Y) (Table 18). Most of the indicators show that semimassive ore samples contain crustal material and are contaminated by graphite schist. In the disseminated ore samples only MnO n and V_2O_3 n give positive evidence of contamination in two of three samples, while isotopes and REE patterns indicate that S, Sm, Nd and REE display the mantle values. C isotopes prove that the graphite in two gabbroic samples from the Upper gabbro zone is of mantle origin, although anomalously high V and Mo contents in one sample indicate the presence of black schist material and S isotopes of both samples evidence of crustal origin.

The indicators of contamination described above were further tested to validate the tools in nickel sulphide exploration. The results summarized in Table 19 indicate the best match for C isotopes and REE, but the number of samples is small. Indicators based on the wholerock chemical analyses, Zn, Mo, V_2O_3 _n, MnO_n and Y, yield contradictory interpretations on contamination and are far too insensitive. The black schist indicator elements work only in massive ore samples.

Of the tested methods, the overall normative sulphide content is the most promising indicator of sulphide saturation. It also gives rise to the interpretation that Bruvann magma was largely contaminated and was sulphur saturated at the time of emplacement. 88 % of the samples give a positive identification in this respect.

Indicators of the Bruvann magma contamination refer to a two-stage process. The first stage of contamination was voluminous, took place at deep level in the crust and caused sulphide saturation of the magma. Even though this event is indicated mainly by O isotopes and by ENd values, if the magma source was depleted mantle, it will explain the overall sulphidesaturated nature of the Råna intrusion (chapter 3.2.2). The second stage of contamination was local and smaller in scale. It took place close to emplacement and explains the final the heterogeneity observed in the concentrations of several elements and isotopes inherited from the crustal material, especially from black schists.

Table 17. Sample by sample interpretation of contamination evidences from single samples. 1=positive evidence of the p	presence
of crustal component, i.e. crustal contamination. 0=no evidence on contamination, blank=no analysis. See indicators in Ta	ble 18.

SampleNo	DDH	From	Zone	Ore	Rock	С	13C	Мо	Zn	$V_2O_3_n$	MnO_n	34S	REE	εNd	Y	\$
9619252	235-120	29.13			BS	1	1	1	1	1	1	1	1	1	1	1
9619423	260-125	183.80	UNoZ	SM	boC	1	1	1	1	1	1	1	1		0	1
9619421	260-125	178.40	UNoZ	SM	pbC	1	1	1	1	1	1	0	1	1	0	1
9619285	235-120	316.40	UPrdZ	SM	bpC	1	1	1	1	1	1	0			0	1
9619464	270-135	207.00	MPrdZ	SM	oMC	0		0	1	1	1	0			0	1
9619419	260-125	175.00	UNoZ	SM		0		1	0	1	1	0			0	1
9619316	235-160	204.30	MPrdZ	D	oMC	0		0	0	1	1		0		0	1
9619325	235-160	302.50	MPrdZ	D	oOC	1		0	0	0	0	0	0	0	0	1
9619315	235-160	198.15	UNoZ	D	BC	0		0	0	1	1	0	0	0	0	1
9619304	235-160	125.50	LNoZ		PoC	0		0	0	0	0		0	1	0	1
9619327	235-160	318.65	UPrdZ		BpC	0		0	0	0	0		0		0	1
9619395	260-125	13.00	LGbZ		OOC	1		0	0	0	0	0			0	1
9619359	235-160	547.00	LGbZ		OR	0		0	0	0	0		1	0	0	1
9619364	235-160	585.50	LGbZ		PC	0		0	0	0	0		0	1	0	0
9619360	235-160	553.40	LGbZ		AbC	0		0	0	1	0		0	0	0	1
9619361	235-160	555.00	LGbZ		pC	0		0	0	0	0		0		0	1
9619387	235-160	772.70	UGbZ		apC	1	0	1	0	1	0	1			0	1
9619385	235-160	756.00	UGbZ		pC	1	0	0	0	0	0	1			0	1

Table 18. Tested contamination indicators. n=number of samples analysed, 1=number of samples with positive identification, 0=number of samples with negative identification. %1=percentage of samples with positive identification. The sample is interpreted to be contaminated if the indicator in the sample is greater(>) or less (<) than the given threshold value. Numbers in parentheses refer to nonlinear contamination equations given below.

Indicator	Threshold		All sa	mples		Barren cumulates					
		n	1	0	%1	n	1	0	%1		
Sulphides (\$)	>0.3%	222	197	25	89	204	179	25	88		
С	≥1% CO ₂	195	29	166	15	178	22	156	12		
$\delta^{13}C$	<-17 per mil	5	3	2	60	2	0	2	0		
Мо	≥2 ppm Mo	222	13	209	6	204	6	198	3		
Zn	>0.012 wt.% Zn (1)	222	26	196	12	204	20	184	10		
$V_2O_3_n$	$>0.07\% V_2O_3_n(2)$	222	34	188	15	204	22	182	11		
MnO_n	>0.2% MnO_n (3)	222	27	195	12	204	16	188	8		
$\delta^{34}S$	<-2 per mil	10	3	7	30	3	2	1	67		
REE	(La/Yb)_N>3 and Eu/Eu*<1.5	11	3	8	27	6	1	5	17		
εNd(T)	<-1 per mil	7	3	4	43	4	2	2	50		
Y	>12 ppm Y	222	10	212	5	204	10	194	5		

(1): Zn wt.%: 1.70E-03*($MgO_n\%^{0.525}$; (2) V_2O_3 n%: 0.00000326*($MgO_n\%^{0.3}$ - 0.000350*($MgO_n\%^{0.3}$ - 0.00903* $MgO_n\%$ + 0.00145; (3) $MnO_n\%$: 0.00000296*($MgO_n\%^{0.3}$ - 0.00042*($MgO_n\%^{0.2}$ + 0.0165* $MgO_n\%$ + 0.00284. Trendlines shown in Figure 34.

6.3.4 Sulphur saturation and chalcophile element depletion

The magmatic character of sulphides and their presence as cumulus phases overall the cumulus sequence are proof of the sulphur-saturated nature of the Bruvann magma throughout the formation of the Basal, Ultramafic and Mafic series. In principle, the ore was formed from a chalcophile element in non-depleted magma, and the segregation of sulphides resulted in chalcophile element depletion in the residual magma (chapter 3).

In Bruvann, the sulphide compositions indicate that both ore types formed from nickel nondepleted magma. On the basis of high Ni# and low Co#, the sulphides of the disseminated ores are primitive (Ni#=83.7, Co#=2.8, Figure 34f). A higher Co# reveals the massive ore to be less primitive than the disseminated ore (Ni# = 80, Co# = 3.9). The ores are, however, depleted in PGE, as shown in Figure 35b.

Bruvann olivines are distinctly Ni-depleted compared with the modelled olivines fractionated from sulphide unsaturated magmas, such as E-MORB (Figure 10e) and tholeitiic magma (Duke and Naldrett 1978, Duke 1979, 1983). Bruvann olivines display a wide range of compositions and do not follow a model trend with decreasing forsterite and nickel content, nor does the trend of the Alter do Chão (chapter 10.3). There are at least four explanations for the scattered compositions of the Bruvann olivines: 1) Analytical uncertainties overrule the real features. 2) Olivines re-equilibrated in metamorphism, and the compositions are not magmatic. 3) Trapped liquid shift changed the composition of olivine. 4) Olivines have not fractionated from one batch of magma in a simple closed system. These possibilities will be discussed in detail in the next chapters.

Table 19. Summary of the tested contamination indicators (Table 18). n=number of samples analysed, 11=number of samples
giving positive identification of contamination for both indicators, 10=number of samples where indicator 1 is positive and 2 is
negative, 00=both negative, 01=negative/positive, Match%=percentage of samples showing similar indication (11 or 00),
+Match%=percentage of samples showing matching where indicator 1 is positive, ++%=percentage of samples where both
positive. Bold : >50% match.

Indicator 1	Indicator 2	n	11	10	00	01	Match%	+Match%	++%
Sulphides	C	195	25	151	15	4	21	14	13
Sulphides	$\delta^{13}C$	5	3	2	0	0	60	60	60
Sulphides	Mo	222	12	185	24	1	16	6	5
Sulphides	Zn	222	24	173	23	2	21	12	11
Sulphides	V_2O_2 n	222	23	174	25	0	22	12	10
Sulphides	MnO_n	222	25	172	24	1	22	13	11
Sulphides	δ ³⁴ S	10	3	7	0	0	30	30	30
Sulphides	REE	11	3	7	1	0	36	30	27
Sulphides	εNd(T)	7	2	4	0	1	29	29	29
Sulphides	Y	222	9	188	24	1	15	5	4
C	$\delta^{13}C$	5	3	2	0	0	60	60	60
C	Mo	194	8	20	161	5	87	24	4
Č.	Zn	195	9	20	149	17	81	20	5
Č.	V_2O_2 n	195	10	19	144	22	79	20	5
C	MnO_n	195	9	20	148	18	81	19	5
C	δ ³⁴ S	7	3	4	0	0	43	43	43
C	REE	3	2	1	0	0 0	67	67	67
- C	εNd(T)	2	- 1	1	0	0	50	50	50
C.	Υ	194	4	25	159	6	84	11	2
δ ¹³ C	Mo	5	3	0	1	1	80	75	60
$\delta^{13}C$	Zn	5	3	0	2	0	100	100	60
δ ¹³ C	$V_{2}O_{2} n$	5	3	0	1	1	80	75	60
δ ¹³ C	$M_{nO} n$	5	3	0	2	0	100	100	60
δ ¹³ C	δ ³⁴ S	5	1	2	1	1	40	25	20
δ ¹³ C	REE	2	2	0	0	0	100	100	100
8 ¹³ C	sNd(T)	1	1	0	0	0	100	100	100
δ ¹³ C	V	5	0	3	2	0	40	0	0
Mo	T Zn	222	7	6	101	18	80	22	3
Mo	VO n	222	10	2	191	22	89	23	5
Mo	$V_2O_3_n$ MnO_n	222	8	5	100	10	80	28	4
Mo	8 ³⁴ S	10	2	3	190	19	69	23	20
Mo	DEE	10	2	0	۰ و	1	00	67	18
Mo	cNd(T)	7	1	0	4	2	71	22	13
Mo	V	222	1	12	200	0	01	5	0
Zn	V.O. n	222	11	12	174	22	91	23	5
Z11 7n	$V_2O_3_n$ MnO_n	222	17	0	186	10	01	47	8
Zii Zn	8 ³⁴ S	10	1	3	4	2	50	47	10
Zii Zn	DEE	10	2	0	4	1	91	67	10
Zii Zn	sNd(T)	7	1	0	4	2	91 71	22	10
ZII Zn	v	222	7	18	4	2	71	25	2
Lii VaOa 19	$M_n O$	222	16	10	194	9 11	91 87	25	7
, <u>203_</u> п V202_п	δ ³⁴ S	10	2	5	2	1	40	25	20
$V_2O_3_n$	REE	11	2	2	2 5	1	-+0	23	18
, <u>203_</u> n V.O. w	sNd(T)	7	∠ 1	2	3 7	2	12 12	20	10
$V_2 O_3 n$	v	222	1	20	ے 192	4	43	20	14
$r_2 O_3 n$ MnO ::	1 8 ³⁴ 8	10	4	50	182	2	04 20	10	2 10
MnO_n	U S DEE	10	1	2	4	4	30 72	13	10
M_nO_n	NEE cNd(T)	7	∠ 1	ے 1	2	1	13	40	18
MnO_n	sind(1)	222	1	1	3	2	5/	25	14
MnO_n \$346	I	222	/	20	192	5	90	23	3
0 S	KEE	4	1	0	2	1	75	50	25
0 S	εNd(1)	3	0	0	2	1	67	U	0
0	Y	10	0	3	7	0	70	0	0
KEE	εNd(T)	7	1	1	3	2	57	25	14
REE	Y	11	0	3	8	0	73	0	0

(1) Bruvann olivines were analysed by electron microprobe using the trace element programme described in chapter 4.3. The coefficient of variation, CV, is 0.9 % for Ni and 0.5 % for Fo content, which are far less than the observed differences.

(2) The metamorphic re-equilibration of olivine with sulphides changes the olivine to one with a lower forsterite content. At Bruvann, the exchange partition coefficient of nickel and iron between sulphide and olivine is about 15 (chapter 11.1.2). The normative sulphide content in the barren olivine cumulates is on average 1 %, whereas in the disseminated ore it is 4 % and the highest content is 7 %. The corresponding change of olivine composition in the ore samples would be a decrease by 0.7 % in Fo-content and 100 ppm decrease of the nickel content, and the shift would be in the direction of fractional crystallisation trend (Figure 4).

(3) Barnes (1986) calculated the effect of trapped intercumulus liquid on the composition of olivine and orthopyroxene cumulus minerals. The equilibration with intercumulus melt causes a compositional shift in cumulus minerals, which depends on the amount and composition of trapped liquid and the chemical compositions of cumulate minerals. The calculation model by Barnes (1986) can be applied directly here, and it indicates that Fo-content of olivine decreases 3-5

percent units in olivine mesocumulates and 5-12 percent units in olivine orthocumulates. For nickel the calculated shift is minor. The amount of olivine at Bruvann cumulates has a weakly positive correlation with Fo-content, but not with nickel in the olivine (Figure 43). For example, in olivine mesocumulates containing 80 % olivine, the forsterite content ranges from Fo₈₁ to Fo₈₇, and the trapped liquid shift cannot be the only reason for the wide variation in forsterite and nickel contents, but may cause a part of the variance and hence will be taken into account in the following.

(4) The most magnesian olivine with Fo_{897} analysed (referred as A olivine) at Bruvann is from the Upper peridotite zone, but this olivine is not rich in nickel (840 ppm). The highest nickel content, 1340 ppm, is recorded in olivine from the Middle peridotite zone with $Fo_{86.8}$ (B olivine). The olivines with low forsterite and relatively high Ni contents compared to model curves are mainly ore samples from the disseminated ore, but not all, as can be seen in the sample indicated by letter D in Figure 44a. The modelled cases, where both A and B olivines are produced from the same parental magma, are shown in Figure 44. Olivine B is produced by fractionation of the olivine alone. The first olivines to crystallise would be at Fo₈₈ and 3000 ppm Ni. Olivine B corresponds the model olivine after 5 % of



Figure 43. a) Analysed forsterite and b) nickel content of olivine versus normative olivine content to illustrate a potential trapped liquid shift.

fractionation. The Ni *vs.* forsterite trend becomes steeper as the amount of sulphides increases, and fractionation of olivine and sulphides together with ratios from 95:5 to 99:1 explains the compositions of most of the olivines. Olivine A would require batch removal of sulphides, where the R factor is 100.

In order to study the depletion of Ni in olivine in different ore types and stratigraphic units, the depletion values were calculated from the model curve. Depletion of Ni, called delta nickel of olivine, or shorter delta Ni (Δ Ni), is the Ni content of olivine predicted on the basis of its *Fo* content by the model curve subtracted by the analysed Ni content at the same *Fo* content.

a) 2) LNoZ 3) UNoZ 3000 ×△+□▽ 3000 4) LPrdZ 5) MPrdZ 6) UPrdZ 7) I GhZ 8) UGbZ Ni of olivine, ppm 2000 -2000 А 1000 1000 (f) \times_{c} B Ч × 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 Mg# of olivine c) 2) LNoZ 3) UNoZ 4) LPrdZ Δ 1000 5) MPrdZ + 6) UPrdZ 7) LGbZ Ni of orthopyroxene, ppm 8) UGbZ ∕₩ п п 100 ∇ +0 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 Mg# of orthopyroxene

Accordingly, the ΔNi values were calculated for modal olivines using the reference curve of the olivines analysed. and similarly for orthopyroxene. The orthopyroxene model curve is an upper envelope curve for the Ni values because modelling with partition coefficients of Beattie et al. (1991) gave too high a nickel content to be reasonable. The ΔNi values presented in Figure 45a-b, show that the ΔNi values of orthopyroxene and olivine as well as the calculated normative olivine are in reasonable agreement. Co# display negative correlation with ΔNi values of olivine and orthopyroxene, as modelling in chapter 3.5 suggests (Figure 45c-d).



Figure 44. a) Olivine analyses of Bruvann, with model curves, which show the evolution of olivine composition in fractional segregation with different olivine to sulphide ratios: a= 100:0, b= 99:1, c= 95:5 and d= 90:10. Line e corresponds to the fractionation of orthopyroxene and olivine in ratios 90:10. The wide variation in forsterite content and production of olivines between the compositions of Fo=88%, Ni=840 ppm (marked by circle and letter A, and called as A olivine in text) and Fo=86.8% and Ni=1340 (B) is explained in the text. Olivine B requires batch fractionation of sulphides with R factor 100. Samples marked with D are disseminated ore samples. b) Co# versus Ni# of Bruvann samples containing cumulus sulphides. Lines a, b and c refer to different ratios of segregating olivine and sulphides as in figure a. c) Compositional evolution of orthopyroxene in the fractionation of olivine (above) and upper envelope curve for ΔNi calculations for orthopyroxene.

The relation of chalcophile depletion to the location of the ore and stratigraphy is illustrated in Figure 46. Below the semi-massive ore olivines and orthopyroxenes are non-depleted, but the Co# is between 10 and 20 suggesting depleted nature of the sulphides. The semimassive ore is undepleted, as shown by the low Co#, but the Lower peridotite zone is clearly depleted and becomes more so towards the disseminated ore as indicated by the olivine composition. A sudden jump to non-depleted takes place in the disseminated ore, but above the ore the next 50 meters are again depleted. In the cumulates of the Upper Peridotite olivine, orthopyroxene and

sulphides are non-depleted to slightly depleted, and this level is maintained throughout the Gabbro zone.

The Mafic series is peculiar since the lowermost olivine cumulate member in each unit is non-depleted or slightly depleted but the uppermost plagioclase cumulate member of only 10-50 meters thick unit is extremely depleted, as shown in Figure 47. The amount of depletion cannot be explained by sulphide segregation and accumulation within the unit. Besides, sulphide accumulations have not been found within the mafic zone.



Figure 45. Comparisons of the indicators of chalcophile element depletion plotted against the delta nickel of analysed olivine: <u>a</u>) Delta nickel of calculated modal olivine ($R^2=0.8$), <u>b</u>) delta nickel of analysed orthopyroxene ($R^2=0.61$), and <u>c</u>) Co# of sulphides ($R^2=-0.4$). <u>d</u>) Co# of sulphides versus delta nickel of modal olivine.

80 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 46. Indices indicating chalcophile element depletion plotted against the stratigraphic height. Ore samples are solid dots and open circles denotes common cumulates.

As a conclusion, the Bruvann magma has been sulphide-saturated, depleted in PGE and a large number of samples are depleted in chalcophile elements indicating segregation and fractionation of sulphide melt mainly together with the olivine. The lower part of the intrusion, from the Norite zone to the central parts of the Upper peridotite zone is moderately to strongly chalcophile element -depleted. The semimassive and disseminated ores are enveloped by a strongly depleted collar around the ore, which exists in all the five drill holes studied. The upper part of the section studied here, the Lower and Upper gabbro zones are weakly to non-depleted with respect to chalcophile elements.

6.4 Geological model

The following geological model on the formation of the Råna intrusion and Bruvann Ni-Cu deposit is based on the results above. The model applicable to exploration, must explain the observations of the ore forming process, such as: 1) the change in the magma composition and crystallisation series, 2) discrepancy in contamination indicators, 3) the PGE-depleted nature of the parental magma, 4) chalcophile element depletion pattern, such as the chalcophile element depletion in the lower part of the stratigraphy, a sudden jump to non-depleted ore, regression back to chalcophile depletion in the Upper peridotite zone and slow recovery back to non-depleted, 5) location of the ore within the Peridotite zone in two horizons.

The Råna intrusion crystallised from relative primitive magma, the MgO_n content of which was ca. 12 wt.%. The magma was sulphur saturated before intruding into the Råna intrusion





Figure 47. One rhythmic unit (M5) of the Lower gabbro zone. The unit starts with 2.5 m thick olivine orthocumulate followed by orthopyroxene-olivine cumulate (5 m), clinopyroxene-plagioclase cumulate (10 m) and plagioclase cumulate (10 m). In the olivine projection of the basalt tetrahedron the lowermost olivine orthocumulate (oOC) plots in the plagioclase field. Composition of the liquid jumps to the field of orthopyroxene (oOC) after which the series develops as in the closed system by crystallising minerals in sequence: olivine-orthopyroxene-clinopyroxene-plagioclase. Clinopyroxene and plagioclase should appear as cumulus minerals almost simultaneously. Fields according to Irvine (1970, 1979) and Irvine et al. (1983).

chamber, which is proved by the overall sulphide saturation of the sequence and zigzag-pattern in the chalcophile element depletion against stratigraphic height. Removal of a small amount of sulphides caused the overall PGE depletion in the studied location. Sulphide saturation was caused by contamination with S-bearing crustal material, which included black schist. Crustal contamination is indicated overall in O isotopes and Sm-Nd isotopes.

The first magma which entered into the intrusion chamber and accumulated in the Lower norite zone, was relatively rich in both Al_2O_3 and SiO_2 probably because of contamination. Since cumulates of the Norite zone are mainly depleted

in base metals, the magma of this series had experienced sulphide segregation, and sulphides were partly removed and lagged behind.

At the end of the accumulation of the Basal series, the magma composition changed abruptly to be more primitive and Mg-rich. The magma dynamics became vigorous and the melt was capable of carrying not only olivine and sulphide droplets but also partly digested crustal fragments. These settled in favourable locations to form semimassive ore, which is heterogeneous, rich in contaminated material, wall rock fragments and sulphides. The incoming magma pulse rich in olivine and sulphides was longlasting and quite voluminous giving rise to the thick olivine cumulates of the Ultramafic series. During short periods of quiescence thin orthopyroxene cumulate interlayers deposited. semi-massive and disseminated The ores originate from the sulphide segregation, which took place during the ascent of magma, and the semi-massive ore deposited at the early stage of the accumulation of the Ultramafic series. Figure 26 and Figure 25 indicate that the semi-massive and disseminated ores actually form a continuous mineralised zone within the Ultramafic series. The zone is here considered to be a layer, which intersects the general lavering like cross-bedding in river and stream sediments.

The wide distribution observed of the Ni# associated with low Co# is in part the result of fractionation of *Mss* from the sulphide melt (shift to high values of Ni#) but mainly due to the small-scale metamorphic re-mobilized of sulphides.

The appearance of the Mafic series denotes a sudden change of the magma composition and it then contained less SiO_2 and more Al_2O_3 and

especially CaO than the magma of the Ultramafic series. The influx was more peaceful than at the beginning of the Ultramafic series. The undepleted nature of the lowermost member and depleted nature of the upper members of the Mafic series (Figure 47) are explained as follows. The new pulse into the magma chamber was not depleted in the chalcophile elements and mixing with residual magma in the chamber caused crystallisation of olivine-bearing cumulates with relatively high tenors of Ni. After complete mixing with the residual magma and fractional crystallisation of olivine, the chalcophile-depleted nature of the residual magma comes up. The upper part of the intrusion, the Quartz Norite series, was crystallised and deposited from the residual magma.

According to the model describe above, the olivine cumulates deposited during the influx of the magma, while the mafic members were accumulated by the fractionation of magma in the chamber. Detailed numerical modelling of the sulphide segregation is done in chapter 11.2.

7 LAUKUNKANGAS

The Laukunkangas intrusion with a related Ni-Cu ore deposit is located in Enonkoski municipality at the south-eastern part of the Kotalahti nickel belt, south-eastern Finland. The intrusion is differentiated, mainly gabbroic (mafic) and the ultramafic portion is small compared to the mafic one. According to the classification of Peltonen (2005) Laukunkangas belongs to the group Ia: intrusions close to the Archean craton margin.

The first discovery of Ni-Cu sulphides in the Laukunkangas intrusion was in 1969. The mineral resource estimation in 1971 after the first drilling campaign ended in figures of 4.5 Mt at 0.33 wt.% Ni and 0.1 wt.% Cu, which were too modest and the case was then rejected (Alopaeus et al. 1986).

Laukunkangas data was re-processed in the late 1970s and there was a reinterpretation of the Nickel Programme data which resulted in the conclusion that the NE corner of the intrusion is the most primitive one and the most potential area for sulphide ore occurrence (Grundström 1980). The second period of diamond drilling started in 1980 and led to the discovery of disseminated ore in peridotite and adjacent massive ore (Grundström 1980, 1985, Alopaeus et al. 1986). Mining was started in 1985 and continued until 1994 and during this period, 6.7 Mt ore at 0.76 wt.% Ni and 0.22 wt.% Cu was processed. The Laukunkangas intrusion was studied bv Grundström (1980 and 1985).

7.1 Geology and subdivision

The northwest-southeast trend oval-shaped Laukunkangas intrusion is 950 m long, 200 m wide and it extends to a depth of 300 m (Figures 48-51). The intrusion is enveloped by migmatised mica gneisses, but at the southeast end, where the ore is located, black schists occur in direct contact with the intrusion. The age of the intrusion is according to U-Pb isotope determination of zircon 1880 ± 3 Ma (Huhma 1986).

The layered structure of the Laukunkangas intrusion is displayed by the variation of cumulate rock types, rhythmic variation of melanocratic and leucocratic layers and fluctuations in the mineral and whole-rock chemistry. Based on the whole-rock Mg content, Grundström (1980) divided the intrusion into three zones: 1) Lower zone, 2) Intermediate zone and 3) Upper zone. The start of each zone was defined by a reversal in MgO content, and the Intermediate zone has a low Cr_2O_3 content. This division is based on drill hole LA-25, but it is not extended to the whole intrusion. Due to difficulties to extend the Grundström's (1980) subdivision to other drill holes and sections and parallel with the other studied intrusions, the stratigraphic subdivision in this study is based on cumulus mineralogy (zones) and base metal geochemistry (subzones).

The Laukunkangas intrusion is divided into a Marginal series and Layered series. The marginal series is mainly noritic in composition, is heterogeneous and contains mica gneiss inclusions and is characterized bv reverse differentiation The marginal series is encountered only in one drill hole EK/LA-25 (Figure 49 and Figure 50).



Figure 48. Geological map of the Laukunkangas region (modified from 1:10 000 geological maps of Outokumpu Mining Oy). Mafic and ultramafic intrusions of the area are named. Laukunlampi intrusion is not outcropped and its dimension is projected.



The Layered series is divided into a Peridotite zone (PrdZ) and Norite zone (NoZ). The Peridotite zone is defined by the presence of olivine as a cumulus mineral. It consists of olivine-, olivine-plagioclase, and olivineorthopyroxene cumulates. The Peridotite zone is located at the south-eastern end of the intrusion and is about 55 meters in its thickest intersection (Figure 50).

The Norite zone overlies the Peridotite zone. It is more than 500 m thick, and consists of

rhythmically-layered orthopyroxene-plagioclase and plagioclase-orthopyroxene cumulates, thus meso- and leuco norites. The Norite zone is subdivided into seven subzones numbered from bottom to the top: i.e. Norite subzone 1 to 7. Each of these subzones consists of rhythmicallylayered plagioclase-orthopyroxene cumulates (pbC and bpC). The criterion of subdivision is the base metal content of the phases, mainly orthopyroxene and sulphides (Table 20).



Figure 50. Geological map of the Laukunkangas intrusion in the vertical cross-section K=34700 of the Laukunkangas mine coordinate system. Ore bodies with Ni content >0.5 wt.% are outlined (based partly on Grundström 1980). Black bars indicate Ni content.

Zone and subzone	Co#	Modal olivine content, %	Note
PrdZ	<5	>25	High Ni# in places (Ni#>85)
NoZ1	<5	<25	High Ni# in places (Ni#>85)
NoZ2	>10	<25	
NoZ3	<5	<25	Low Ni# in places (Ni#<45)
NoZ4	5-10	-	
NoZ5	10-20	-	In the disseminated ore Co# 4-10
NoZ6	20-30	-	
NoZ7	>30	-	

Table 20. Classification parameters in subdivision of the Laukunkangas intrusion.

The Norite subzone 1 (NoZ1) overlies the Peridotite zone, but in many places it is missing, and subzone 2 or 3 lie directly on the Peridotite zone. Norite subzone 1, about 20 m thick consists of layered plagioclase-orthopyroxene and plagioclase cumulates, which locally contains some relics of olivine grains. It is characterised by high Ni content in sulphides and mafic silicates. The Ni content of orthopyroxene is above 250 ppm and Co# of sulphides is 3-4. The Mg# of orthopyroxene decreases from 84 at the bottom to 79 at the top. Norite subzone 2 can be found only in three drillholes EK/LA-16, -23 and -25 at the SE end of the intrusion lying on the Norite subzone 1 as shown in Figure 50 and Figure 51. Subzone 2 is about 10 meters thick and consists of plagioclase-orthopyroxene and plagioclase cumulates. The Norite subzone 2 is clearly depleted in chalcophile elements compared to subzones 1 and 3: Ni content of orthopyroxene is about 50 ppm and Co# of sulphides is above 7 (generally about 20).





Norite subzone 3 lies on subzone 2 or directly against the enveloping gneiss (Figure 50 and Figure 51). It is about 40 meters thick and is mineralogically and in chemical composition almost identical compared to subzone 1. The difference is noted in the Ni#: in the Norite subzone 1 the average Ni# is 78 and varies between 55 and 98, extending to high values, while in subzone 3 the average is 65 and ranges from 13 to 86, i.e. towards lower Ni# (Figure 53).

Norite subzone 4 is a 140-metre thick rhythmical unit consisting of plagioclaseorthopyroxene and orthopyroxene-plagioclase cumulates. Co# continues to grow from 5 with an increasing stratigraphic height to 10. The variation in the Ni# is from 72 to 81. There is a distinct change in the mutual ratios of plagioclase and orthopyroxene in the middle of the Norite subzone 4 in drill hole LA-25. The lower part of the subzone 4 is rich in plagioclase while the upper part is dominated by orthopyroxene (Figure 52). The change is reflected in the chemistry: $Al_2O_3_n$ and CaO_n contents drop and $Cr_2O_3_n$ and *MgO_n* rise (Figure 52). Grundström (1980, 1985) set the boundary between the Intermediate and Upper zones here, but such a change could not be found in the adjacent drill holes and sections. The change in the mineral proportions has only a minor effect on sulphide chemistry with constant Ni#, and therefore both units: leucocratic pbC and mesocratic bpC, are included in the subzone 4.

Norite subzone 5 dominates the intrusion in the surface section (Figure 49). Normative plagioclase content in the placioclaseorthopyroxene cumulate has increased from subzone 4 and is here between 40 and 55. Generally, Co# is higher than in the subzone 4: between 10 and 20, but within the deep ore (see later) it decreases to <5 (Figure 51). In the Norite subzone 6, Co# increases to >20 and in the Norite subzone 7 to >30. The rock type is plagioclaseorthopyroxene cumulate, and the normative plagioclase content increases gradually upwards in the stratigraphy (Figure 52).

7.2 Chemistry and mineralogy

The chemistry of the Laukunkangas cumulates is controlled by four important cumulus phases: olivine, orthopyroxene, plagioclase, and sulphides, and intercumulus material as shown in Figure 52. The MgO_n content is highest (>20%) in the peridotite zone, where olivine is the cumulus mineral. The existence of plagioclase is reflected in $Al_2O_3_n$, CaO_n , Na_2O_n and SrO_n . In the Norite zone, the orthopyroxene content is reflected in $Cr_2O_3_n$ and MgO_n .

Igneous minerals and mineral textures are well preserved in Laukunkangas. Olivine is commonly altered to serpentine and orthopyroxene to amphibole, but plagioclase is practically fresh. Olivine occurs as a cumulus mineral only in the Peridotite zone; in the Norite subzones 1 and 3 it as relictic grains resorbed occurs hv orthopyroxene. Composition of olivine varies from Fo₇₂ to Fo₇₇ and nickel from 800 to 1600 ppm. Compared to Bruvann the olivines of Laukunkangas display a narrow range of Ni

content and they are poorer in Fo content (Figure 53). Orthopyroxene occurs as a cumulus mineral in almost the whole intrusion, and therefore, it is a good mineral to follow the compositional evolution of magma. The general trend of orthopyroxene is the decrease in both Mg# and Ni content (Figure 54). The Mg# varies in a wide range from 37.6 to 81.9. Minor reversals exist mainly in the zone boundaries. The Ni content of orthopyroxene in the Norite zone 2 is low, 40-125 ppm, which is exceptional in the general decreasing evolution trend. The anorthite content of plagioclase fluctuates around 60% showing no correlation with the amount of normative with plagioclase or the composition of orthopyroxene. Chrome spinel occurs as an accessory mineral in the Peridotite zone. It has a low Cr/(Cr+Al) (0.2-0.4) and Mg# (Figure 31, p. 61). The zinc content of chromites in two ore samples is high: 1.0-2.8 wt.% Zn.

7.3 Nickel-copper ore

The most important Ni-Cu ore bodies of Laukunkangas occur along and above the basal contact against black schist. A massive sulphide ore at the contact changes gradually to network dissemination in olivine cumulate. The massive sulphide veins extend to the footwall gneisses. Low-grade small orebodies can be found further away from contact within Norite zones 1, 3 and 5.

The Ni-Cu ores of the Laukunkangas intrusion are subdivided according to the host rock as follows: 1) ore hosted by the Peridotite zone (the main orebody, "Päämalmio"), 2) ore hosted by Norite subzone 1 and 3 (the slope orebody, "Rinnemalmi"), 3) ore hosted by gneisses, (the Leo orebody, "Leonmalmi"), and 4) low-grade ore hosted by Norite zone 5, (the deep orebody "Syväpirote" and "Mäkimalmi").

The Peridotite zone hosted nickel ore located at the east end of the intrusion is a typical network dissemination, where the cumulus olivine grains are surrounded by a sulphide matrix composed of pyrrhotite, pentlandite and chalcopyrite. The Ni tenor is higher than in the other ore types, 3.1-6.8 Ni_SF%.

In places Peridotite ore extends to the Marginal zone and to the footwall mica gneiss and black schist. Graphite is a common accessory mineral in these ores as well as in the ore types hosted by norites (Figure 55). In norites, graphite occurs as flakes of 100-500 µm in length mainly in the interstices of plagioclase and orthopyroxene, but also as inclusions in them (Figure 55). On microscopic scale, a thin section of the amount of graphite correlates roughly with sulphides. The presence of graphite is reflected in whole-rock chemistry by an increase in the contents of V_2O_3 n, Mo, MnO n and Zn as illustrated in Figure 56. The concentrations of these elements are also high in a barren black schist sample shown as a reference in Figure 56.

88 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 52. Variation of selected elements and mineralogy as a function of stratigraphic height. Drill holes included in the stratigraphy column are: LA-23, -25, -27 and -30. Normative minerals have been calculated from volatile- and sulphide-free composition.



Figure 53. Ni vs. Mg# plot of <u>a)</u> olivine and <u>b)</u> orthopyroxene in Laukunkangas. All microprobe analyses. Fields show the compositional field of minerals in Bruvann. The curve in figure b is for reference and is an exponential curve fitted on the Laukunkangas datapoints.



Figure 54. Variation in mineralogy against the stratigraphic height in Laukunkangas. Opx refers to the orthopyroxene analysed.

90 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 55. Photomicrographs of Laukunkangas. a) Olivine-sulphide cumulate, the ore of the Peridotite zone. Sample 9619672, EK/LA-38/188.1-188.6 m, o\$C, PrdZ, \$ = 34.4 %, Ni = 1.62 wt.% b) Sulphide-orthopyroxene-plagioclase cumulate with intercumulus phlogopite, ore of the Norite zone. Sample 9619665, EK/LA-38/145.15-145.65 m, \$bpC, NoZ1, \$ = 46.0 %, Ni = 2.23 wt.%. c) Barren orthopyroxene-plagioclase cumulate. Sample 9619656, EK/LA-30/250.48-250.98 m, bp(\$)C, NoZ5, \$ = 0.39 %, Ni = 0.019 wt.%. d) Graphite schist inclusion in the plagioclase-orthopyroxene cumulate of the Norite zone. Coarse recrystallised graphite occurs in the interface between the inclusion and the cumulate. Sample 9619614, EK/LA-25/174.35-174.85 m, pb\$C, NoZ3, \$ = 8.3 %, Ni = 0.30 wt.%. e) Partly digested graphite schist inclusion in plagioclase-orthopyroxene cumulate. Between the inclusion and the cumulate hybridic rock exists that is rich in phlogopite, amphibole and sulphides. Sample 9619646, EK/LA-30/119.63-120.12 m, pb\$C, NoZ5, \$ = 6.5 %, Ni = 0.018 wt.%. In all figures sulphides consist of pyrrhotite, pentlandite and chalcopyrite.



Figure 56. Elements indicating the presence of graphite schist plotted against MgO_n contents. C = barren cumulates, GN = wall rock gneisses, GPH = graphite schist, M = marginal zone ore, NO1/3 = ores of Norite subzones 1 and 3, NO5 = ore samples of Norite zone 5 and PRD = ores of the Peridotite zone and. In figure a, the discrimination line of Bruvann is drawn for reference.

To illustrate the controls of the disseminated ore in Norite zone 5, drill hole LA-30 is discussed in more detail. LA-30 intersects the Norite subzones 5, 6 and 7, but the structural interpretation of the intrusion in that part is somewhat questionable (Figure 51). Co# is high in the Norite subzones 6 and 7, but abruptly it decreases to values <10 and fluctuates between 2 and 10 for 200 meters, after which the Co# increases back to a level typical for Norite subzones 6 and 7 (Figure 57). The low Co# is associated with the increase in sulphide (ca. 10 wt.%) and nickel content (0.4 wt.% as an average). Intervals of low Co# display anomalously high contents of V_2O_3 n, Zn, MnO n and Mo as depicted in Figure 57. In polished thin sections, graphite and remnants of graphite schist can be found (Figure 55).

The Ni tenor in barren cumulates decrease parallel with the MgO_n content (Figure 58a). The ore samples of Norite subzones 1 and 3, however, are not in keeping with the normal

trend, but all have higher *Ni tenor* than barren cumulates of the Norite zone. Co# vs. Ni# diagrams in Figure 58b and c illustrate the compositional variations in different ore types. Peridotite hosted ores form a well-defined trend towards the origin of the diagram with relatively high Co#. The ore samples of Norite subzone 5 plot above these, whereas the other ore types display lower Co#, but also they show a linear trend towards the origin. The order of the ore types by decreasing Co# is: (ore of the) Norite subzone 5, Peridotite zone, Norite subzones 1 and 3 and the Marginal zone. A graphite gneiss sample shown as a reference in Figure 58c display still lower Co# (1.8) than the ore samples.

The total PGE contents are low at Laukunkangas, *PGE tenor* is around 200 ppb. The highest *PGE tenor* of 935 ppb was recorded in an ore sample from the footwall gneiss. All the ore samples display a negative Pt anomaly when normalised against the chondrite as shown in Figure 59 (Papunen 1986, 1989).

7.4 Genetic considerations and geological model

The parental magma of the Laukunkangas intrusion is evolved and silica-rich. The highest analysed forsterite content of olivine is Fo77 in olivine-orthopyroxene cumulate containing 40% normative olivine, 30% normative orthopyroxene and 20% normative plagioclase. The compositional shift of olivine caused by a trapped intercumulus shift has evidently been significant and lowered the forsterite content up to 10% according to model calculations after Barnes (1986). Regression to TiO_2 n=0 in TiO_2 n vs. Fo content of peridotites (Figure 60b) suggests Fo₈₇ for the initial olivine composition, but a more conservative estimate of Fo₈₀ with 1500 ppm Ni is taken to represent the initial magmatic olivine. The average CaO/Al₂O₃ is 0.5, but in the Peridotite zone it is 0.6. The Al₂O₃/TiO₂ is ca. 10 in the Peridotite zone.

The Laukunkangas olivine cumulates, plotted in a clinopyroxene projection of the basalt tetrahedron in Figure 60c, show that the olivine initiated the crystallisation of Laukunkangas. The first olivine cumulates plot on the olivineplagioclase field suggesting a crystallisation order olivine-plagioclase-orthopyroxene, but quite soon the path bends towards orthopyroxene. The change in the ratio of plagioclase to orthopyroxene is seen in olivine cumulates by the decrease in the ratio of normative plagioclase to normative orthopyroxene parallel with normative olivine content (Figure 60a). Orthopyroxene and plagioclase appear almost simultaneously as cumulus phases and in the Norite zone they accumulate rhythmically as the composition of melt has meandered between plagioclase and orthopyroxene saturation.



Figure 57. The variation of selected element in drill hole LA-30 shown in Figure 49 and Figure 51.

94 Geological Survey of Finland Bulletin 402 Pertti Lamberg





Figure 58. Composition of sulphides in different ore types versus barren cumulates of different stratigraphic units. **a)** Ni tenor, field of different ores are shown. **b)** Co# vs. Ni# diagram. Elongated field is the ore in the Peridotite zone and Norite subzones 1 and 3 where a roundish field shows the composition ore hosted by the Norite subzone 5, Marginal zone and footwall gneisses. Note that y axis is in log-scale. **c)** Co# vs. Ni# diagram of different ore types. Lines are fitted to go through origin. GPH=graphite schist, M=marginal zone ores, NO1/3 = ores of the Norite subzones 1 and 2, NO5 = weak dissemination in the Norite zone 5, PRD = ores of the Peridotite zone.



Figure 59. Chondrite normalised spidergrams of Laukunkangas ore samples. Note the negative platinum anomaly, and differences in Ni to Co ratio.





The normative sulphide content of the Laukunkangas intrusion is high throughout the stratigraphy; the average of barren cumulates (Ni<0.5 wt.%) varies from 0.5 wt.% in the Marginal zone to 5.2 wt.% in the Peridotite zone. 90% (n = 127) of barren cumulate samples contain cumulus sulphides. The high normative sulphide content is proof of the sulphide-saturated nature of the Laukunkangas magma throughout the formation of the intrusion.

Laukunkangas shows identical contamination features with Bruvann. Graphite is ubiquitous and correlates roughly with sulphides. Hybridic rocks and remnants of graphite schist are associated with anomalously high contents of $V_2O_3_n$, Mo,



Figure 60. a) Ratio of normative plagioclase to (normative plagioclase + orthopyroxene + clinopyroxene) in the Peridotite zone decreases as the amount of normative olivine in olivine cumulates decreases. This refers to change in the intercumulus mineral ratios in the Peridotite zone, which in turn is an indication of change in magma composition. b) Indicator of trapped liquid content, TiO₂ n vs. Fo content of olivine (analysed). Poor correlation indicates a trapped liquid shift and Fo content of approximated TiO_2 n = 0 points to the initial olivine Fo₈₈. A more conservative estimate Fo₈₀ is used in model calculations. c) Laukukangas samples plotted on clinopyroxene projection of the basalt tetrahedron illustrate the change in the magma composition to more SiO₂-rich and favouring orthopyroxene at the expense of plagioclase. Fields according to Irvine (1970, 1979) and Irvine et al. (1983).

MnO_n and Zn in the ore and its surroundings. The sulphur isotope study does not fully prove that model, since average δ^{34} S of norite is only slightly negative (-0.23 per mil). In graphite schist the average δ^{34} S is -2.6 per mil and the values overlap with those of norite; see Papunen and Mäkelä (1980). ϵ Nd(T) of the Laukunkangas gabbronorite is +0.5 (sample by L. Grundström, analysis by H.Huhma; Huhma, pers. comm.).

Laukunkangas intrusion displays strong chalcophile element depletion in cumulates lying above the ore. The overall high normative sulphide content in cumulates indicates that sulphides have occurred in the silicate liquid as immiscible droplets. The different subzones represent various liquid increments in the system considerable and amounts of sulphides fractionated from the silicate liquid whose major element composition contemporaneously evolved from the crystallisation of olivine to fractionation of orthopyroxene with plagioclase. The magma intruding into the Laukunkangas magma chamber was sulphur-saturated, and a small portion of early removed sulphides had depleted it in platinum-group elements. The sulphide saturation upstream was caused by black schist contamination. Detailed numerical modelling of the sulphide segregation is presented in chapter 11.2.

The first magma pulse of the Laukunkangas intrusion was primitive, non-depleted in base metals (Ni# = 81 and Co# = 3.3, Table 21) and capable of carrying large amounts of sulphide droplets. The major element composition of the first pulse was unlike that of the latter ones. The olivine grains and sulphide droplets carried by the magma settled down at the bottom of the intrusion to form a massive-semimassive-disseminated ore.

The composition of replenishing magma pulses

shifted from the olivine-plagioclase-orthopyrone crystallisation order to olivine-orthopyroxeneplagioclase when the Norite zone was accumulated. The compositional shift was mainly caused by contamination. Thus the early magma, which carried more sulphides than the latter one, was less contaminated in terms of major elements. Norite zone 1 was formed from magma, which was as primitive as the magma of the Peridotite zone in terms of composition of sulphides i.e. Ni# and Co# (Figure 61). The magma was highly contaminated and carried graphite schist fragments, graphite and sulphide droplets with cumulus orthopyroxene and plagioclase crystals. Sulphides accumulated in favourable depression structures where also partly digested black schist xenoliths were deposited. Norite subzone 2 formed from the residual magma of Norite subzone 1. The magma chamber was replenished at the beginning of the accumulation of Norite subzone 3. The magma composition shifted back to subzone 1. Sulphide enrichments associated with remnants of black schist and graphite formed in places.



Figure 61. Box and whisker diagram of <u>a)</u> Co# and <u>b)</u> Ni#. Barren cumulates with cumulus sulphides shown. For explanation of the box and whisker diagram see terms and nomenclature in chapter 20.

Gradually, the magma depleted in chalcophile elements and Norite subzone 4 crystallised from the residue of the magma of the Peridotite zone subzones 1-3. The and Norite sulphide enrichments in subzone 5 deviate from the linear evolution trend. The presence of graphite schist fragments, anomalous contents of $V_2O_3 n$, MnO n, Mo, Zn and C and the exceptionally low Co# are explained by a high amount of graphite schist component in Norite subzone 5. This could be due to floating and settling of the fragments at their present levels, or similarly to Norite subzones 1 and 3, they injected suddenly into the chamber during the formation of subzone 5.

Norite subzones 6 and 7 were formed by fractional crystallisation of plagioclase and orthopyroxene and sulphide from the magma, where significant amounts of sulphides and orthopyroxene were removed. Fluctuations in Ni# and Co# indicate, however, that sulphide fractionation and related base metal depletion did not take place *in situ* but rather in the upstream flow and the system remained open. In the broadest sense what is seen in the Laukunkangas intrusion is actually a reflection of the segregation of sulphides and stratification which has taken place in the feeder.

Table 21. Estimated compositions of the parental magmas, % = wt.%.

	Laukun-	Stormi	Ekojoki	Rausen-	Rörmyr-	Posion-	Porras-	Alter do	Alter do
SiO ₂ %	53.8	48.2	46.8	47.2	53.2	45.5	49.7	46.2	20 A
TiO ₂ %	0.57	0.35	0.49	0.30	0.54	0.41	0.54	0.54	0.61
Al ₂ O ₃ %	11.2	5.5	6.6	7.7	8.1	5.2	12.1	3.8	12.0
$Cr_2O_3\%$	-	-	0.73	-	_	0.95	_	0.25	0.00
FeOtot%	16.6	18.6	19.5	19.6	10.8	22.2	12.9	21.9	7.9
MnO%	-	-	0.16	0.26	0.36	0.23	-	0.34	0.06
MgO%	7.2	12.5	11.4	9.5	12.0	12.0	6.6	23.5	5.7
CaO%	6.6	12.1	11.6	10.5	10.7	11.0	15.0	1.4	21.5
Na ₂ O %	1.849	0.509	0.764	0.892	0.743	0.490	1.204	0.467	1.142
K ₂ O %	0.515	0.613	0.371	2.576	1.991	0.416	0.532	0.207	0.207
P2O5%	0.193	0.051	0.071	0.211	0.089	0.064	0.070	0.032	0.026
Sum	98.6	98.4	98.6	98.9	98.6	98.5	98.6	98.6	98.5
Ni ppm	140	150	147	96	370	45	53	297	236
Cu ppm	29	41	48	41	15	9	15	-	-
Co ppm	48	49	49	40	66	85	29	-	-
Al ₂ O ₃ /TiO ₂	19.5	15.9	13.5	25.5	14.9	12.7	22.3	7.0	19.7
CaO/Al ₂ O ₃	0.6	2.2	1.8	1.4	1.3	2.1	1.2	0.4	1.8
Ni#	82.8	78.5	75.4	70.1	96.1	83.3	77.9	-	-
Co#	22.1	20.4	20.1	22.6	14.6	61.2	29.9	-	-
Observed values	in cumulate	es							
Al ₂ O ₃ / TiO ₂	10.5	10	13.3	11.7	20	11.5	13	10.7	7.5
CaO/ Al ₂ O ₃	0.6		0.6			0.3	2.1	0.3	2
Max Fo%	77	83.9	81.9	78.9	89.6	80.7	79.8	89.3	84.9
Ni of Ol ppm	1383	1493	1465	961	3673	448	530	2970	2360
Ni# (Sulph)	70.5	64.4	60.6	54.3	92.7	71.6	63.3	-	-
Co# (Sulph)	3.1	2.9	3.2	8.3	1.4	23.5	10.8	-	-

Fe/Mg ratio of the liquid was determined from olivine accoriding to $K_{D(Fe-Mg)}^{Olivine-liquid} = 0.30$ (Roeder and Emslie 1970). The

ratio of other main elements to MgO were determined using the regression analysis of olivine cumulates as described by Chai-Gang and Naldrett (1992). Absolute contents were estimated by finding the solution where the oxide sum is 98.5 (1.5 wt.% for trace elements and volatiles).

8 STORMI

The Stormi intrusion is located in southwestern Finland in the Vammala Nickel Belt about five km east of the centre of town of Vammala. Stormi represents in this study an ultramafic fertile intrusion. Häkli et al. (1979), Häkli and Vormisto (1985), Mäkinen (1984, 1987), Marshall and Mancini (1994, 1995a, 1995b), Mancini (1996) Mancini et al. (1996) and Peltonen (1995a and b) have studied the Stormi intrusion and nickel deposit.

The Stormi Ni-Cu deposit was discovered in 1960 as a result of exploration initiated by a discovery of a sulphide-bearing peridotite sample sent by a layman. Full-scale exploitation of the deposit was started in 1978 and continued until 1994. A total of 7.6 million tonnes of ore grading 0.68 wt.% Ni and 0.42 wt.% Cu was mined from the Stormi deposit.

8.1 Geology of the area

The Stormi area is mainly composed of migmatised, arenaceous intensely metasedimentary rocks cut by synkinematic granodiorites and quartz diorites as shown in Figure 62 (Aarnisalo 1998, Kilpeläinen and Rastas 1992). Metamorphism took place in the equilibrium field of garnet and cordierite ± sillimanite at a temperature above 580°C (Kilpeläinen 1998, Mancini 1996). Common graphite gneiss interlayers in migmatized gneiss, ranging from some tens of centimetres to several tens of metres in thickness are easily recognized on geophysical maps. The graphite content is commonly a few percent, but locally may reach 20 wt.%. The sulphur content is 2.7-5.7 wt.%, i.e. 7-16 wt.% normative sulphides, and the sulphide mineral assemblage is pyrrhotite-chalcopyritesphalerite.

Mafic and ultramafic rocks occur as deformed and dismembered dykes and boudinaged bodies in migmatites of the Stormi area. The bowlshaped ultramafic host rock of the Stormi Ni-Cu deposit is located in the core of a large F_2 antiform (Kilpeläinen 1998, Kilpeläinen and Rastas 1992); it is the largest ultramafic intrusion of the area with one kilometre as the maximum diameter. According to Häkli et al. (1979) the footwall contact is subconform against the supracrustal rocks in the substrate. According to Kilpeläinen (1998) ultramafic rocks probably intruded as horizontal sills before D_2 folding.

In order to define the possible contact heat effect of the intrusion Kilpeläinen (1998) and Kilpeläinen and Rastas (1992) studied the chemical compositions of garnet in the gneissic wall rocks in a 190 m long profile away from the contact of the Stormi intrusion. Neither the mineral compositions nor the thermometry could indicate a contact effect, and the values were compatible with those obtained elsewhere in the Stormi subarea. Also, a detailed study of garnet grains two metres away from the contact did not show any signs of growth in several stages and in conditions. According different p-T to Kilpeläinen (1998) the lack of contact metamorphic features dates the intrusion event prior to the peak of regional metamorphism, at pre D₂ age. An intrusion geologically equal to Kylmäkoski is either of D₁ age or older (Kilpeläinen 1998). Mancini and Marshall (1995) studied the metamorphic zoning at the borders of felsic dykes intersecting the Stormi intrusion and concluded that the dykes are related to D_2 deformation in the upper amphibolite-lower granulite facies conditions, i.e. 700-730 °C and 4-5 kbar (Mancini 1996, Peltonen 1990, 2005).





Figure 62. Geological map of the Vammala area (modified from the geological 1:10:000 maps of Outokumpu Mining Oy). The studied intrusions Stormi, Posionlahti and Ekojoki are shown as well as some other drilled ultramafic intrusions.

D₁ structures started to evolve immediately after the 1.93-1.91 Ga rifting stage (Lahtinen 1994). The migmatisation of high-grade metamorphic sedimentary rocks at Vammala started simultaneously with the evolution of the earliest deformation structures resulting in trondhjemitic veining and segregation parallel to the layering and S₁ schistosity (Kilpeläinen 1998, Aarnisalo 1988). The peak of thermal metamorphism (800 °C) was reached in southwestern Finland during the intrusion of lateorogenic potassic granitoids (1840-1830 Ma) (Korsman et al. 1984, Schreurs and Westra 1986, van Duin 1992, Väisänen et al. 1994).

Uusiniitty, Vammala and Komeronlahti formations, earlier referred to as cortlandites

(Mäkinen 1984, 1987, Häkli et al. 1979), are here referred to as metamorphic equivalents of picritic metalavas.

Peltonen (1995a, b, c and d) studied the genesis of the Stormi Ni-Cu ore and concluded that the key process in the ore formation was the contamination of the magma by country rock sulphides. Evidence came from the following observations: high Se/S ratios of the ore points to crustal source of Se and S, zinc content of chromite is higher in Stormi than in the barren ultramafic intrusions in the vicinity, and REE and LILE patterns indicate of crustal contamination. Sulphur isotopes in Stormi are, however, uniform δ^{34} S varying between -2 and +2, which is almost in the range of magmatic values (+1 - +2).

8.2 Subdivision and chemistry

The Vammala ultramafic complex is shaped like a subhorizontal bowl, it is up to 300 meters and the longest dimension is 1.5 km (Figures 64-65). The ultramafics of the Vammala complex were called by Häkli et al. (1979) as upper, intermediate and lower ultramafic layers, but according to Peltonen (1995a and b) these layers are not genetically related. The lowermost layer hosts Ni-Cu sulphide ore and is an ultramafic igneous cumulate origin while the middle one is an older picritic volcanite. The whole system with three ultramafic units is here called the Vammala ultramafic complex (Figure 63).

<u>The upper serpentinite</u> of the Vammala complex is about 70 meters thick and consists of olivine and olivine-clinopyroxene cumulates of the crystallisation series olivine-clinopyroxeneorthopyroxene-plagioclase (Figure 65 and Figure 66). The texture differs from other ultramafics since large (3 mm) euhedral clinopyroxene grains are surrounded by fine-grained (200 μ m) cataclastic olivines. CaO/Al₂O₃ of the most



Figure 63. Subdivision of the Vammala ultramafic complex and Stormi intrusion



Figure 64. Interpreted stratigraphic map of the Vammala ultramafic complex. Modified after Häkli (1979) and geological maps of Outokumpu Mining. The lines indicate profiles of Figure 65 and Figure 67. (Finnish coordinate system KKJ2).



Figure 65. Schematic map on the distribution of the rock types in the section 2447900 mE looking west. Modified after Häkli (1979) and geological maps of Outokumpu Mining.

102 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 66. Photomicrographs of Stormi. **a)** Neoblastic olivine pseudomorphs in serpentinite of the upper ultramafite. Sample 9619494, TY-183/39.09-39.59 m, oMC, \$ = 0.17 %, Ni = 0.21 wt.%. **b)** Metamorphic amphibolite of the middle ultramafite. Sample 9619499, TY-183/89.0-89.5 m, \$ = 0.06 %, Ni = 0.21 wt.%. **c)** Olivine-sulphide cumulate. Sample 9619524, OKVA-280/73.35-73.85 m, oC, DuZ1, \$ = 23.5 %, Ni = 1.44 wt.%. **d)** Olivine- cumulate with poikilitic orthopyroxene which has been altered. Sample 9619535, OKVA-762/22.50-22.75 m, o(\$)OC, DuZ4, \$ = 0.40 %, Ni = 0.018 wt.%. **e)** Olivine cumulus grains enclosed by brownish magmatic amphibole. Sample 9619529, OKVA-280/96.15-96.65 m, o\$MC, DuZ1, \$ = 20.8 %, Ni = 1.35 wt.%. **f)** Ore textures in reflective light. Sample OKVA-220/110.20 m. The sulphide assemblage is pyrrhotite (Po) - pentlandite (Pn) – chalcopyrite (Ccp), also in Figures c and d.

DuZ1 DuZ2 DuZ3 Du74 MPrdZ-MPxZ Ore

Legend





magnesian olivine cumulates is low: 0.25-0.5, and Al₂O₃/TiO₂, 3.5, is characteristic compared to olivine cumulates of the other ultramafics of the complex (Figure 68). Low value of the Al₂O₃/TiO₂ of the cumulates is derived from a high titanium content which indicates the high TiO₂ content of the magma as well. The content of alkalis, Na_2O n and K_2O n as well as Al_2O_3 n are low. Sulphides are scarce; the average normative sulphide content is 0.2 wt.%. Sulphides of the upper serpentinite are primitive (Ni#=90) and non-depleted (Co#=7). The upper ultramafic unit is a separate cumulate body, which crystallised from a different parental magma than the metapicrite unit and the intrusion. Textures derive from metamorphic recrystallisation.

The metapicrite of the Vammala complex consists of layers of metamorphosed picritic volcanic rocks with metasedimentary intercalations. The total thickness is about 100 m (Figure 65 and Figure 67). The MgO n content ranges from 22 to 27 wt.%, and the normative cumulus name for the MgO n-richest rock is clinopyroxene-orthopyroxene cumulate. The minerals: amphibole, olivine and green spinel are metamorphic (Figure 66). CaO/Al_2O_3 and Al₂O₃/TiO₂ are close to the values of the Stormi intrusion but in CMA diagram metapicrite differs from the intrusion and the upper serpentinite (Figures 68 and 69). The TiO_2 n, Al_2O_3 n,

SrO n, Na_2O n, ZrO_2 n, P_2O_5 n, Y and REE content of the metapicrite layers is high compared to the cumulates of other two ultramafics with same MgO n content. TiO_2 n in particular, is significantly higher than in the Stormi intrusion (Figure 68).

The Stormi intrusion is up to 100 meters thick and is here subdivided into a Layered series and Marginal series. The Marginal series is from 2 to 20 meters thick and it envelops the intrusion on both sides. It consists of pyroxenitic and peridotitic cumulates. The Marginal series is subdivided into three subzones: a Marginal pyroxenite subzone against gneiss (MPxZgn), Marginal peridotite subzone against gneiss (MPrdZgn), and a Marginal peridotite subzone against metapicrite (MPrdZpic). In places where the intrusion is in contact with mica gneiss - as it commonly is (Figure 65 and Figure 67) - the Marginal series consist of both peridotitic (MPrdZgn) and pyroxenitic (MPxZgn) rocks, the latter against the country rock. Cumulates are rich in normative orthopyroxene and phlogopite (Figures 70 and 71). They commonly exhibit high concentrations of lithophile elements (TiO2 n, Al2O3 n, ZrO n, Y), alkalis (Rb₂O n, K2O n, SrO n, BaO n, Na2O n), REE, V_2O_3 n and P_2O_5 n, but the low content of MnO n. Sr/Ca ratio is anomalously high.



Figure 68. Variation in the chemical composition of Vammala Ultramafic Complex: upper serpentinite, metapicrite and Stormi intrusion in drill hole TY-183.



Figure 69. Samples of the Vammala ultramafic complex plotted on CMA diagram. Metapicrites (STO/MPIC) plot in distinct field whereas the cumulates of the upper serpentinite (STO/SRP) and Stormi intrusion (STO/I) plot along the fractionation trend towards clinopyroxene and CaO apex. Gneisses (GN) are rich in Al₂O₃_n, and the part of the STO/I cumulates, which point towards gneisses, are from the Marginal pyroxenite.

In places where the intrusion is in contact with metapicrite, like the hanging wall contact in NW part (Iivari), the Marginal series consists of peridotitic olivine-clinopyroxene cumulates only (MPrdZpic). Chemical composition of the contact rock against metapicrite is intermediate between the olivine cumulate in the central part of the intrusion and metapicrite. Compared to the Marginal series against gneiss, the Marginal peridotite subzone against picrite displays a lower 100*orthopyroxene/pyroxenes ratio (<50, Figure

DuZ1

MPrdZgn

MPxZgn

71), and a lower concentration of $Al_2O_3_n$ (1.3-2.2 wt. % vs. 1.8-4.4 wt.%,) and higher content of Cr_2O_3 *n* and *MnO n*.

An almost 100-metre thick Layered series consists of olivine, olivine-chromite, olivinesulphide. olivine-sulphide-chromite and cumulates and according to cumulus mineralogy it is dunitic in composition. On the basis of sulphide chemistry, it is divided into four subzones, which are called Dunite subzones 1, 2, 3 and 4 from bottom upwards, respectively. Dunite subzone 1 consists (DuZ1) mainly of olivine-(chromite)-sulphide meso-adcumulates, but chromite is not a cumulus mineral in all localities as shown in Figure 71. Orbicular texture (Häkli et al. 1979, Papunen 1980, 1985a, 1985b) is occasionally encountered in Dunite subzone 1. The content of incompatible elements $(Al_2O_3 n_1)$ TiO_2 n, Na_2O n, K_2O n, P_2O_5 n, etc.) is as on average lower than in the other subzones, which is due to the higher olivine content. The Co# is below 4. The characteristic for this subzone is high Ni#, commonly above 75, although it varies widely between 20 and 100. Dunite subzone 1 is commonly rhythmically layered in terms of sulphide composition; layers with low Ni# alternate with layers of high Ni# as depicted in Figure 70. The upper boundary of subzones 1 is set at the last sample, above that the Ni# remains under 75 (Figure 74, Table 22).

Zone and subzone	Normative	olivine	Ni#	Co#	Note
	content, %				
MPrdZpic	30-50				Against picrite
DuZ4	>50			>4	
DuZ3	>50		50-75	<4	
DuZ2	>50		0-75	<4	

0-100

<4

Against mica gneiss

Against mica gneiss

>50

30-50

<30

Table 22. Subdivision parameters of the Stormi intrusion.



Figure 70. Variation of selected elements against the stratigraphic height in the Stormi intrusion. Complete stratigraphic column was built from the drill holes TY-183 (DuZ1, DuZ2 and MPxZpic), TY-170 (DuZ2, DuZ3 and MPxZpic) and TY-179 (DuZ4).



Figure 71. Normative (B-norm) mineral contents and MgO_n content. Note that chromite is a minor cumulus phase (boundary 0.6%) in the dunite zone, but despite a clear stratigraphic boundary where the chromite disappears as a cumulus mineral (Figure 70), each subzone has areas where chromite is a cumulus phase and areas where it is not.
Dunite subzone 2 (DuZ2) consists of olivine-(chromite)-sulphide ortho- and mesocumulates (Figure 71). The normative olivine content decreases from the average of 67% in subzone 1 to 60% in subzone 2. In Dunite subzone 2, the Co# is low, <5, and Ni# ranges widely between 0 and 75 with prevailing Cu-rich variants are characteristic for subzone 2 (Table 22).

Dunite subzone 2 turns to subzone 3 with the change of the sulphide fraction from Cu-rich (Ni#<50) to Cu-poor (N#=50-75). Co# is still below 4 (Table 22). Rocks of the Dunite subzone

3 are olivine-(chromite)-sulphide orthocumulates and the normative amounts of olivine and intercumulus material are at the same level as in subzone 2 (Figure 71).

Dunite subzone 4 (DuZ4) consists of olivine(chromite)-sulphide cumulate. The value of Co# above 4 (up to 18) distinguishes it from subzone 3. The normative sulphide content is lower and the amount of intercumulus material and thus the contents of incompatible elements are higher than in the other subzones.

8.3 Mineralogy

The primary igneous mineralogy of the Stormi intrusion has significantly changed in metamorphism. Primary cumulus textures are still visible, but olivine has been almost completely altered to serpentine and magnetite (Figure 66, p. 102). Olivine grains form a cumulus network in a matrix of intercumulus minerals and sulphides. The textures indicate that orthopyroxene has occurred as poikilitic intercumulus grains especially in the Dunite subzones 1 and 2. In the ore poikilitic grains can be seen in the ore even with the naked eye (Figure 66, p. 102).

Despite intense alteration, relict cores of primary minerals are available for electron microprobe mineral analyses. The *Fo* content of olivine varies mainly from 73.4 to 87.4 % and Ni between 500 and 1800 ppm. In the Ni *vs. Fo* diagram, olivines form a cluster around the reference line of fractionation of olivine from tholeiitic magma in sulphide undersaturation (Duke 1979). Compared to Bruvann, the olivines of Stormi are generally poorer in Fo, but richer in Ni and they display a more narrow range of Ni (Figure 72). The Ni content of olivine has a weak negative correlation to the normative sulphide content of sample, when the sulphides exceed 2% (Figure 72). The *Fo* content of olivine decreases

parallel to the amount of olivine (Figure 72). In stratigraphy, the *Fo* content decreases from 81.8% in subzone 1 to 79.8% in subzone 2. After reversal to 81.7% in subzone 3, the *Fo* content decreases quite abruptly to 78.5% in the top of subzone 4. The Ni content of olivine shown in Figure 72 follows the *Fo* content: from values above 1000 ppm in the subzones 1 and 2 it decreases to 800-1000 ppm in subzone 3 and further to 600-800 in subzone 4.

Orthopyroxene and clinopyroxene imitate the compositional features of olivine (Figure 72 and Figure 73). Chromite in Stormi occurs as minute cumulus grains enclosed in olivine, in olivineintercumulus interface and in sulphides (Lamberg and Peltonen 1991, Peltonen 1995c). The finest grains of chromite are those enclosed in olivine, and grains in olivine-intercumulus interfaces show the most pronounced zoning from Cr# 0.6 to 0.25 (Peltonen and Lamberg 1991). Stormi chromite of is compositionally similar to that of Bruvann (Figure 31a). The zinc content is moderately high, ranging in cores of grains from 0.36 to 1.61 wt.% Zn and it remains quite constant as a function of stratigraphic height (Figure 73).



Figure 72. Chemical composition of <u>a</u>) olivine, <u>b</u>) orthopyroxene, <u>c</u>) clinopyroxene and <u>f</u>) amphibole: besides textures, the high K_2O and TiO_2 contents of amphibole are evidence of primary igneous nature. All are microprobe analyses.



Figure 73. Variation of compositions of minerals as a function of stratigraphic heights in the Stormi intrusion; <u>a)</u> Fo content of olivine, <u>b)</u> Ni content of olivine, <u>c)</u> Mg# of clinopyroxene, <u>d)</u> Zn content of chrome spinel, <u>e)</u> Ni tenor, <u>f)</u> Cu tenor, <u>g)</u> Ni#, and <u>h)</u> Co#. Chemical composition of minerals figures a-d are analysed by electron microprobe.

These include Al₂O₃, whose content in amphibole

is up to 14 wt.%, TiO₂ (up to 1.6 wt.%), Na₂O (up

to 3 wt.%) and K_2O (up to 1.2 wt.% Figure 72f).

Plagioclase was not found in the Stormi samples,

and the normative plagioclase in Figure 71 refers

to a primary magmatic amphibole, whose amount

is almost twice as high as the normative

The brownish amphibole that occurs in the intercumulus space and partly replaces the pyroxenes is interpreted as a primary magmatic mineral (Figure 66, cf. Mancini et al. 1996). Proof comes from the amphiboles high contents of elements, which have been incompatible in the early crystallising olivine and pyroxenes and therefore have enriched in the silicate liquid.

8.4 Nickel-copper ore

plagioclase.

The orebodies of the Stormi: Sotka-Korvalampi in the SE part and Iivari (also called Syvämalmi, Deep ore) in the NW part are located mainly in Dunite zone 1, and therefore hosted by olivine-chromite and olivine cumulate (Figure 65 and Figure 67). In places the ore extends to Marginal peridotite, Marginal pyroxenite against gneiss and even to the gneiss as massive veins. Sulphide paragenesis is a pyrrhotite-pentlanditechalcopyrite. For a more detailed description on sulphide mineralogy, see Häkli et al. (1979).

The *Ni tenor* of the ore varies widely from 3 to 12.5% (average 6.3%) and *Cu tenor* from 0 to 12% (average 4.9%), respectively. The Ni# of the ore varies from 10 to 98 whereas the range for the positively related Co# is narrower from 0.7 to 4.4 (Figure 74). Composition of the sulphide fraction of the ore samples differ from barren cumulates by their lower Co# and wide variation in Ni# (Figure 74). The PGE content of the ore is very

low, at maximum 500 ppb and *PGE tenor* 5 ppm, respectively. Half of the total PGE is Pd. In spidergram (Figure 75), PGE show highly depleted characteristics compared to chondritic concentrations of Ni, Cu and Cu. The distribution pattern for PGEs is flat for Ir, Ru and Rh, but Pt has a strong negative anomaly (in 3 of the 7 analysed samples the platinum content was below the detection limit). Pt+Pd to Ru+Ir+Os ratio varies between 2 and 14 and has no correlation to Ni# (not shown).

Encouraged by the results of Bruvann, the volatile- and sulphide-free compositions of the ore samples were studied and compared with barren cumulates, but no differences were detected. La/Yb ratio is close to the mantle value $(La_N/Yb_N = 0.6-1.6)$. The content of the elements considered indicators of graphite schist $(MnO_n, V_2O_3_n, Zn, Mo, C)$ are at the same low level both in the ore and barren cumulate samples.

8.5 Genetic considerations

The parental magma of the Stormi intrusion is determined in the same way as earlier in the Bruvann case. The highest *Fo* content of olivine in a sulphide-poor olivine cumulate sample is 82.3%. The *Fo* content versus calculated the trapped liquid correlation gives Fo_{84} for the primary olivine (Figure 77). Olivine cumulates form a relatively well-defined regression trend, but the assumption that these rocks represent a mixture of olivine + intercumulus liquid in

different proportions will yield a magma, which is unrealistically rich in CaO and poor in Al_2O_3 (~6 wt.%). The plot of olivine cumulates in basalt tetrahedron projection from plagioclase (Figure 76) reveals that the composition of magma has slightly changed from the crystallisation order of olivine-orthopyroxene-clinopyroxene in Dunite subzones 1-2 to olivine-clinopyroxeneorthopyroxene in Dunite subzones 3 and 4. The shift is supported by observations on the presence

112 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 74. Compositional variation of the sulphides of the Stormi intrusion indicated by Co# and Ni#. <u>a)</u> Co# vs. Ni# of all samples with cumulus sulphides. The field of ore samples is indicated by a field. <u>b)</u> Co# versus Ni# of samples having cumulus sulphides outside the ore proper. <u>c)</u> Box and whisker diagram of Co# illustrate the variation in different subzones, all samples with sulphides are shown. <u>d)</u> Box and whisker diagram of Ni#; conditions as in Figure c. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20.

of poikilitic orthopyroxenes in subzones 1 and 2 and poikilitic clinopyroxene in subzones 3 and 4 (Figure 76). The presence of poikilitic pyroxenes explains the large variation of CaO/Al₂O₃ from 0.1 (oCb) to 6.5 (oCa) in olivine cumulates. An almost constant Al_2O_3/TiO_2 of 11 refers to common basaltic magma (Table 21). The shift in the magma composition may be due to crustal contamination, but observations supporting this are few. Peltonen (1995b, 1995d) based his statement on the contamination of the zinc content of chromite, sulphur isotopes (which overlap with sulphur isotopes of mantle and crust) and the Se/S ratio.

The sulphide mineral paragenesis pyrrhotitechalcopyrite-pentlandite and their occurrence in the intercumulus space are evidence of primary magmatic sulphides (Figure 66). In Stormi, 96 % (i.e. 105 of 109) of barren cumulate samples contain cumulus sulphides (i.e. more than 0.3 % normative sulphides). The average normative sulphide content is 2.8%, and sulphides are ubiquitous through the stratigraphy, although the lowermost Dunite subzones 1-2 are the richest. Sample/Chondrite CI (Nadrett & Duke 1980,Palme & al 1981)



The abundances of sulphides in Stormi indicate that the magma of Stormi has been sulphursaturated throughout the formation of the intrusion.

Most of the compositional variation of olivine Fo content in the Stormi intrusion can be explained by the trapped liquid shift, as illustrated in Figure 77a. The regression gives decrease of 2.6 % in Fo content for each 10 % increase in the amount of trapped liquid, which is the same value as estimated by Barnes (1986) for olivine cumulates. The ΔNi of the olivine was tentatively calculated against the curve of olivine fractionation in sulphide undersaturation by Duke (1979) (Figure 72b). The poor correlation with Co# and calculated ΔNi values indicates that the trapped liquid shift has significantly changed the Fo content of olivine. Because the correlation between the amount of trapped liquid and Fo content is good, and 75 % of olivines provably were originally between Fo₈₃ and Fo₈₅ and were modified by the trapped liquid shift, only Ni content of olivine is used in the following. A moderate correlation between the Co# and Ni content of olivine demonstrate that the conclusion is fair.

The Co# versus Ni# diagram in Figure 74a-b reveals details of the ore-forming process. Firstly, the pattern of ore samples indicates that ore has experienced chalcopyrite remobilisation and possibly also the fractionation of *Mss* from the sulphide melt. The linear shift towards Co# = 0







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Figure 76. Olivine cumulates of the Stormi intrusion plotted in the plagioclase projection of the basalt tetrahedron. Fields according to Irvine (1970, 1979) and Irvine et al. (1983). Lines 1, 2, 3 and 4 are fitted straight lines from the olivine apex for each dunite subzones 1-4, respectively. In the subzones 1-2 olivine cumulates suggest crystallisation olivine-orthopyroxene-clinopyroxene-(plagioclase) order while in subzones 3 and 4 the order is olivineclinopyroxene-orthopyroxene-(plagioclase). A number of samples from the subzone 1 and 2 plot on olivineorthopyroxene side of the diagram referring to olivine cumulates with poikilitic orthopyroxene while in subzones 3 and 4, the samples tend to plot along olivineclinopyroxene join referring to olivine cumulates with poikilitic clinopyroxene.

and Ni# = 0 and the converse drift towards high Ni# values are exactly as modelled in Figure 12b for the removal of Cu-rich portion from the primary sulphides. Secondly, the trend of the barren cumulates towards a higher Co# indicates the segregation of sulphides in the presence of



high sulphide to olivine ratio. Thirdly, the positive correlation of Co# and Ni# in the barren cumulates indicates that the partition coefficient between sulphide and silicate liquids is larger for



Figure 77. <u>a)</u> Estimated amount of trapped liquid (calculated from aluminium content of rock and estimated aluminium content of the melt) versus analysed Fo content of olivine.

b) Poor correlation with Co# and Δ Ni of olivine is interpreted to be mainly due to re-equilibration with trapped liquid (and sulphides). Δ Ni of olivine has been calculated against the tholeite model line of Duke (1979) shown in Figure 72a.

<u>c)</u> Analysed Ni content of olivines versus Co# of samples containing cumulus sulphides.

Cu than for Ni. The pattern of barren cumulates in Stormi resembles case B of chapter 3.5. Numerical modelling of the sulphide segregation is done in chapter 11.2.

8.6 Geological model

The narrow range in the *Fo* content of olivine and monotonous mineral compositions of the cumulates require an open magmatic system, constant fresh silicate liquid replenishment and a wash-away of the residual. Stormi magma has been sulphur saturated throughout the formation of the intrusion, as evidenced by high overall normative sulphide content of the cumulates.

A sulphur-saturated basaltic magma intruded into the Stormi chamber with high flowrates

enabling sulphide droplets, olivine grains and orbicules to remain suspended. The sulphide saturation of the magma had occurred deeper in the crust in the interaction with graphite schist as suggeted by Peltonen (1995a, b, c and d) according to crustal Se/S ratio and sulphur isotope ratios and high Zn content of chromite. Besides sulphur, the content of zinc increased in contamination. Some sulphides were left behind in this process or already earlier, causing an overall PGE depletion in magma.

Magma interacted with country rocks in the Stormi chamber and the Marginal series was formed. Due to larger compositional difference with gneiss, both the Marginal pyroxenite and peridotite zones were formed in footwall contact while in the hanging wall contact only a thin peridotitic subzone was formed.

The sulphide/olivine ratio was high during the formation of subzones 1 and 2. The sulphide and olivine were settled in the Stormi chamber while more than 99 % of the residual liquid of the subzones 1 and 2 went through the chamber. Also, the trapped liquid was able to react with the

new fresh magma, and poikilitic orthopyroxene was formed.

The amount of sulphides decreased in subzone 3. Magma composition changed slightly, causing clinopyroxene to crystallise before the olivine. The intrusion system remained open, but the amount of trapped liquid increased to 5-10. In subzone 4, sulphides were depleted in chalcophile elements and the Co# was between 8 and 18. The chalcophile element -depleted nature and lower Fo and Ni# of subzone 4 suggests that it crystallised from the residual of subzones 1-3. Since subzone 4 is homogeneous, the intrusion was continuously replenished by fresh magma of constant composition. The intrusion remained open till the end.

An amphibole crystallised from the trapped liquid instead of plagioclase, which is due to the high water content of the magma. During cooling, the *Mss* segregated from the sulphide liquid and both Ni-rich and Cu-rich layers were formed. Curich residual sulphide liquid penetrated into gneiss.

9 SUBECONOMIC INTRUSIONS

The subeconomic intrusions include three Svecofennian intrusions: Ekojoki and

Rausenkulma in Finland and Rörmyrberget in Sweden.

9.1 Ekojoki

The Ekojoki intrusion, c. 3 km northwest of the Vammala complex (Figure 62, p. 99) is located partly under lake Rautavesi and has only one outcrop. Three unmined mineralisations have been located at above 150 m level and a total of 1.2 Mt ore grading 0.47% Ni and 0.31% Cu has been evaluated (Vesanto and Katajarinne 1984).

The Ekojoki intrusion was originally studied by Outokumpu exploration at the time of the discovery of the Stormi ore. Erratic boulders and weakly mineralised outcrop led to diamond drilling and between 1961 and 1964 seven holes were drilled. The exploration was continued in 1973 with seven new holes and 1983-1984 with additional 21 drill holes. Several weakly mineralised intersections were met (Vesanto and Katajarinne 1984). The result of the resource estimation was too modest to start mining, although the closest tunnel end of the Vammala mine was some 1000 m southeast of Ekojoki.

Ekojoki was included in the works of Mäkinen (1984, 1987), and Peltonen (1995a, b, c and d) studied the Ekojoki intrusion together with Stormi, Posionlahti and Murto. On the basis of

geochemistry and mineralogy Peltonen (1995b) concluded that the contamination of black schist triggered the ore formation in Vammala area intrusions, and high PGE contents in Ekojoki, unlike Stormi, were because Ekojoki magmas did not intersect thick black schist layers, and did not experience sulphide segregation on deep level of the crust, but the sulphides were assimilated *in situ*, and the major source of sulphur was the closely associated black schist.

9.1.1 Geology, petrochemistry and mineralogy

The geological environment of the Ekojoki intrusion is generally similar to Stormi and Posionlahti. The intrusion lies conformal in migmatised metaturbidites, i.e. mica gneisses. The northeastern side of Ekojoki mica gneisses are garnet-bearing, and graphite- and sulphidebearing intercalations are common, as in the eastern and southern contact of the intrusion (Figure 78). Metapicrite, similar to that in Stormi (Uusiniitty metapicrite), with amphibolites and graphite gneisses, are witnessed on the western side of the intrusion. In Ekojoki, the intrusion and metapicrite are not in direct contact, but separated by mica gneisses and intersecting granite veins.

The Ekojoki intrusion is an almost vertical plate, 280m long, 20-120 meters thick and extends at least 200 m below the surface. Contacts between the intrusion and mica gneisses are sheared, and frequently the contact areas are rich in granite veins. Although the intrusion seems to be conformable with mica gneisses, at least some of the contacts are probably tectonic especially on the western side of the intrusion. The strongest shear zone with mylonites is located between metapicrite and the intrusion, and Vesanto and Katajarinne (1984) considered that the shear and fault zones detached the south edge of the intrusion with associated mineralisations



The cross-section of the Ekojoki intrusion is almost symmetrical in structure: the most primitive olivine cumulates are found in the centre of the intrusion, and a fractionation series develops in both directions via the olivineclinopyroxene cumulates to pyroxene cumulates at the margins (Figure 79). Since the intrusion is rather zoned than layered, the structure is described using a selected representative profile (Figure 79), which represents the variation in mineralogy and chemical composition of the rock against structural distance from the eastern contact (0 m) towards west.

On both sides of the intrusion the contacts towards mica gneiss are sheared and tectonised. The contact zone in the intrusion is, however, most probably primary, because the rocks next to the contact are more fine-grained than cumulates and hybridic in composition. Therefore, the sections studied are here treated as a whole and if contacts are tectonised, faulting has taken place along the contact itself.

The subdivision of the Ekojoki intrusion is based on the cumulate types (Figure 80). Heterogeneous contact rocks, some metres thick, form the Marginal series (MS), which is for descriptive purposes called Marginal pyroxenite zone (MPxZ). Chemically, it can be distinguished from its MgO-poor nature, MgO<26% (Figures 81 and 82). Compared to the other cumulate types of the Ekojoki intrusion, the Marginal pyroxenite is rich in SiO_2_n (>50%), V (> 400 ppm), Y (>6 ppm) and LREE (e.g. La >10 ppm).





Figure 81. Variation of selected elements in stratigraphic profile of Ekojoki (drill hole EJ-17, zero point is the eastern contact). Plotmarks according to subzones. The orbicular peridotite layer is marked as O in the chromium diagram.



Figure 82. Al₂O_{3_n} (in a) and CaO_n (in b) versus MgO_n reveal the difference in the chemical composition of the outer and central Dunite subzones.

The appearance of olivine as cumulus mineral marks the beginning of the central series (CS), which is divided into two zones. The peridotite zone is located next to the Marginal series, and is defined by olivine and pyroxene as cumulus minerals. It is about 10 meters thick. Two subzones were established according to the main pyroxene: a clinopyroxene-dominating Peridotite subzone (PrdZa) and an orthopyroxenedominating Peridotite subzone (PrdZb). Chemically the Peridotite zone can be distinguished by its MgO *n* content, which varies from 24 to 32 wt.% (Figures 81 and 82). The disappearance of pyroxene cumulus mineral marks the beginning of the Dunite zone (DuZ) in the centre of the intrusion.

The dunite zone forms more than half of the intrusion and it includes the mineralisation. The Dunite zone, with more than 32 % MgO, is divided into two subzones. The outer Dunite subzone (DuZo) differs from the central Dunite subzone (DuZc) in intercumulus mineralogy. The major intercumulus mineral changes from the amphibole in the central part of the intrusion to clinopyroxene in the outer parts of the Dunite zone. It follows from the mineralogy that the outer subzone (DuZo) is generally poorer in $Al_2O_3_n$ (<2.5%) and richer in CaO_n (>3.5%)

than the central Dunite subzone (DuZc, Figures 81 and 82). The boundary between the outer and central Dunite subzones can be set in a CaO/Al₂O₃ of 1.5, though overlapping exists. Besides Al_2O_3 n the central Dunite subzone (DuZc) is richer in TiO_2 n, SrO n, K_2O n, and P_2O_5 n, and poorer in SiO₂ n and CaO n than the outer subzone. Base metals and sulphur contents are higher in the central Dunite subzone due to the presence of sulphides. The content of lithophile elements, such as LREE, Y and Th, are higher in the central Dunite subzone than in the outer Dunite subzone in any given MgO ncontent. Worthy of mention is the fact that both Marginal pyroxenite and central olivine-cumulate are rich in REE, especially in LREE, Y, and P_2O_5 n and have a high La/Yb ratio (Figure 84).

In mineral textures, the Ekojoki intrusion is almost identical to Stormi, with the exception that the amount of sulphides is smaller and chromite is missing or is not as abundant. As in Stormi, plagioclase is missing and the textures and composition suggest that the amphibole The primary igneous mineral. amount of indicated amphibole (as by normative plagioclase) is higher in the central Dunite subzone than in the Stormi intrusion.



Figure 83. Variation of normative mineralogy, CaO/Al₂O₃ and 100*plagioclase/ (plagioclase+orthopyroxene+clinopyroxene) in stratigraphic profile of Ekojoki.

Sample/Mantle McDonough et al. 1991



Figure 84. Mantle normalised REE pattern of three Ekojoki cumulates, Rausenkulma and Posionlahti. From Ekojoki the sample from central Dunite subzone shows higher La/Yb and La/Sm ratio than the sample from the outer Dunite subzone. In the middle of the central Dunite subzone a 1.5-meter- thick layer of oribicular peridotite was identified. Texturally it is similar to Stormi orbicular peridotite with the important difference that the orbicules in Ekojoki are surrounded by chromite rim (Figure 85). In chemical composition, the orbicular peridotite can be recognized by a high chromium content, which is up to 1.7 wt. % Cr_2O_3 _n (Figure 81).

Olivines of Ekojoki and Stormi are compositionally similar (Figure 86a). In Ekojoki the composition of cumulus olivine varies from $Fo_{72.7}$ to $Fo_{81.9}$ and the Ni content in the Dunite zone from 800 to 1400 ppm. Olivines of the central Dunite subzone are on average richer in nickel than in the outer Dunite subzone. The chrome spinel of the Ekojoki intrusion occurs as minute inclusions in olivine, while zoning is



Figure 85. Photomicrographs of Ekojoki <u>a</u>) Whole section image of orbicular peridotite; field of view is $3.4 \times 2.1 \text{ cm}^2$. Four orbicules with chromite (Chr) rim. Orbicule on right has olivine-chromite cumulate (ocC) core enveloped by olivine cumulate (oC). Sulphides (Sulph) are encountered almost entirely outside the orbicules. <u>b</u>) Closer view of the chromite rim of the orbicule. Sample 9619549, VM/EJ-17/102.3-102.8 m, oc\$MC, DuZc, \$ = 1.44 %, Ni = 0.18 wt.%. <u>c</u>) Olivine-sulphide cumulate. Olivine has altered to serpentine + magnetite (Ol->Srp+Mgt). Sample 9619551, VM/EJ-17/126.1-126.6 m, o\$C, DuZc, \$ = 7.5 %, Ni = 0.40 wt.%. Sulphides in all figures consist of pyrrhotite, pentlandite and chalcopyrite.



Figure 86. Variation of <u>a-b</u> olivine and <u>c-d</u>) sulphide fraction composition in stratigraphic profile. Olivine composition according to electron microprobe analyses.

weak. Cr/(Cr+Al) decreases from the Peridotite zone via the outer Dunite subzone to the central Dunite subzone, and since Zn has a negative correlation with Cr#, the Zn content of spinel is highest in the central Dunite subzone, 1.0 wt. % Zn as an average (Figure 88b).

9.1.2 Nickel-copper mineralisation

The Ekojoki Ni-Cu mineralisations are hosted by the central Dunite subzone (DuZc) both in the northern and southern parts of the intrusion. Mineralisation is of low-grade, containing c. 0.5 wt. % Ni, and mineral paragenesis is pyrrhotitepentlandite-chalcopyrite. Graphite is encountered occasionally with sulphides (Figure 87). The sulphide-free chemistry volatileand of mineralised samples differ from corresponding non-mineralised cumulates by their anomalous high contents of Al_2O_3 n and TiO_2 n. This is due to differences between central and outer Dunite subzones, but in the central Dunite subzone proper, the mineralised samples do not differ from the barren ones. The black schist indicator



Figure 87. Ekojoki, sulphides , pyrrhotite-pentlandite (Pn) -chalcopyrite, with graphite (Gph). Sample 9619545, VM/EJ-17/90.3-90.8 m, oOC, central Dunite subzone, = 11.1, Ni = 0.75 wt.%.

elements (*MnO_n*, *V*₂*O*₃*_n*, Zn, C) and U and Cs display similarly low concentrations both in mineralised and barren samples.

In the Co# versus Ni# diagram (Figure 88c) the Ekojoki mineralised (Ni>0.5 wt.%) samples plot in the field of the Stormi ore samples. Similarly as in Stormi the samples plot in a linear trend towards the origin (Co# = 0, Ni# = 0) and linearly away from it, but the range in Ni# in Stormi is narrower. The Co# of the outer Dunite subzone and the Peridotite zone are higher than in the central Dunite subzone (Figure 86 and Figure 88d).

The PGE contents of the Ekojoki mineralisation are high compared to other studied intrusions (Figure 89a). In the four samples, the total PGE content varies from 0.3 ppm to 1.6 ppm and the *PGE tenor* from 4.2 ppm to 14.6 ppm. The chondrite normalised PGE distribution pattern (Figure 89b) of the Ekojoki sulphide fraction resembles that of komatiites (Naldrett 1989).

9.1.3 Petrogenetic considerations

The parental magma of Ekojoki is close to that estimated in Stormi (Table 21). The shift in the composition of the magma during the emplacement of the intrusion can be seen in Ekojoki, too. The central Dunite subzone, which mineralisation. hosts the suggests the order olivine-orthopyroxenecrystallisation clinopyroxene, while the outer Dunite subzone shows а crystallisation order olivineclinopyroxene-orthopyroxene as depicted in the plagioclase projection of the basalt tetrahedron in Figure 91. The variation in the Fo content of Ekojoki olivine can be explained mainly by a trapped liquid shift, similarly to Stormi. A negative correlation exists between the amount of estimated trapped liquid and Fo content of olivine, as shown in Figure 90a. Regression through the olivine cumulates suggests a higher Fo content for the central Dunite subzone than for the outer Dunite subzone (Fo_{84} vs. Fo_{86}).



Figure 88. <u>a)</u> Ni content of olivine versus Fo content of Ekojoki, electron microprobe analyses. The field of Stormi olivines and compositional evolution trend of olivine fractionation from tholeiitic liquid in sulphide under-saturation after Duke (1979) are indicated. <u>b)</u> Box and whisker diagram of the Zn content of chrome spinel, Ekojoki. <u>c)</u> Composition of sulphides in terms of Co# versus Ni#. Field of Stormi ore samples and Ekojoki samples containing more than 0.5 wt. % Ni is drawn. <u>d)</u> Box and whisker diagram of Co# of barren (Ni<0.5%) cumulates containing more than 0.3 wt. % sulphides. For explanation of the box and whisker diagram see terms and nomenclature in chapter 20.



Figure 89. a) Total PGE tenor versus normative sulphide content of the case study targets. Ekojoki is rich in PGE compared to other intrusions. b) PGE spidergram of Ekojoki samples, all from the central Dunite zone.



Figure 90. Estimated amount of trapped liquid (from aluminium content) versus analysed Fo content of olivine of Ekojoki cumulates. A line taken from Stormi illustrates the trapped liquid shift of olivine, if the original composition was Fo_{84} . <u>b</u>) Analysed Ni of olivine versus Co# shows poor negative correlation.





Figure 91. Ekojoki olivine cumulates plotted on the plagioclase projection of the basalt tetrahedron. Regression through the central Dunite subzone (DuZo) samples points to a crystallisation order of olivine-orthopyroxene-clinopyroxene, while regression of outer Dunite subzone (DuZo) points to a crystallisation order of olivine-clinopyroxene-orthopyroxene. Fields according to Irvine (1970, 1979) and Irvine et al. (1983).

The more silica and alkali-rich nature of the central Dunite subzone can be the result of crustal contamination. A normalized REE-pattern and Ce to Yb ratio show that the Marginal pyroxenite and the central Dunite subzone are enriched in LREE compared to the outer subzone and the Peridotite zone. Other geochemical features that support the contamination hypothesis of the central Dunite subzone, are the higher contents of lithophile elements in a given MgO_n content: TiO_2_n , $P_2O_5_n$, Y, Zn and Th. The Zn content of the chromite is higher in the central Dunite subzone: 1.0 wt. % Zn compared to 0.7 wt. % Zn in the outer subzone and in the Peridotite zone.

The outer Dunite subzone and the Peridotite zone crystallised from the same parental magma and produced cumulates in the series oC, oaC, ab(o)C. Marginal pyroxenite is considered to be a hybrid rock after mixing of this magma and wall rock. Central Dunite subzone was crystallised in the order olivine-orthopyroxene-clinopyroxene (plagioclase). This second magma differed from the parental magma of the outer subzone and evidently was contaminated with crustal material.

A positive correlation with the Co# and Ni# refers to higher sulphide-silicate partition coefficient of Cu than that of Ni. The shift towards the origin in the Co# vs. Ni# graph suggests remobilisation of Cu-rich veins or *Mss* fractionation.

Both magma types were sulphide-saturated, but the magma responsible for the outer subzone was slightly chalcophile-depleted, because the amount of Co# is c. 10 (Ni# = 75). Towards the central Dunite subzone both Co# and Ni# decrease, which indicates that the magma has developed to become more primitive. In the central Dunite subzone, the wide variation of Ni# combined with a low Co# indicates fractionation of *Mss* or remobilisation of chalcopyrite. Ni-rich sulphides are located in the outer part of the central Dunite subzone, while the very centre of the central Dunite subzone consists of olivine-sulphide cumulate, where the sulphides are primitive and rich in Cu.

9.1.4 Geological model

A well-defined and relatively flat positive trend in the Co# versus Ni# indicates that Ekojoki cumulates have fractionated from a sulphidesaturated magma. If the Ekojoki body has crystallised from the margins inwards, as the symmetrical structure infers, the first magma to enter into the chamber and crystallise along the wall-rock contacts corresponds in composition to the residual of the magma injected in the centre of the body. This can be explained by the feeder character and stratified magma chamber upstream in the intrusion. The sulphides fractionated in the feeder and the residual melt of the process erupted from the feeder forward into the Ekojoki chamber (intrusion). The eruption of the primitive, sulphide-saturated magma from the feeder into the Ekojoki intrusion ended the magmatic evolution of the Ekojoki intrusion. Fractionation of *Mss* from the sulphide liquid has most probably taken place in the intrusion, since the high partition coefficient calculated for Cu indicates the residual character of the fractionated sulphide melts.

9.2 Rausenkulma

The Rausenkulma intrusion is located in Kokemäki, south of the Vammala Ni belt. The intrusion is here classified as an ultramafic subeconomic intrusion, hosting a small and low-grade mineralisation. Grundström and Lehtonen (1995) reported the exploration of the Rausenkulma prospect, but there are no published studies.

The Rausenkulma exploration was initiated by the discovery of a low-grade mineralised erratic boulder by a layman and the intrusion was discovered in 1989. The drilling campaign in Rausenkulma and Rausenkulma II intrusions started in 1990 resulted in a total of 27 drill holes until 1994 (Grundström and Lehtonen 1995). A small nickel sulphide occurrence was delineated and the preliminary geological mineral resource estimate was ca. 40 000 tonnes of ore at 0.68 wt. % Ni and 0.95 wt. % Cu. Due to modest results the exploration was closed in 1994.

9.2.1 Observations

The geological environment of the Rausenkulma intrusion is quite identical to that of the Vammala area intrusions. Migmatized mica gneisses with graphite- and sulphide-bearing intercalations dominate the bedrock. About 1 km southwest of the intrusion the Proterozoic bedrock is overlain by Subjotnian Satakunta sandstone and diabase dikes (Figure 92).

The Rausenkulma intrusion is layered and displays a rhythmic layering of the crystallisation order olivine-clinopyroxene-orthopyroxeneamphibole-plagioclase. A common feature to the intrusions of the Vammala area is the lacking of plagioclase as intercumulus mineral and its late appearance as a cumulus mineral. Primary minerals have suffered alteration. Olivine has been mostly altered to serpentine and magnetite. Clinopyroxene is mainly replaced by amphibole, which is interpreted to be a late magmatic





replacement due to textural and compositional evidences (Figure 93). Calcium-rich and calciumpoor compositional amphibole variants can be recognized. The calcium-rich amphibole occurs as a) exsolution droplets in clinopyroxene, b) subhedral and partly poikilitic grains in the resorbing intercumulus space cumulus clinopyroxene, and c) subhedral cumulus grains containing inclusions of relic clinopyroxene (Figure 93). The high Al₂O₃, TiO₂, CaO and Cr₂O₃ content of the amphibole indicate that a Ca-rich amphibole formed in the reaction clinopyroxene + residual liquid \rightarrow amphibole. The Ca-poor amphibole is interpreted as a secondary mineral, since it occurs as prismatic grains replacing primary cumulus minerals.

The intrusion is subdivided into two series: a marginal series and layered series (Figure 94). The layered series is divided into three zones: a rhythmic Peridotite zone, Pyroxenite zone and a Gabbro zone. The marginal series, *i.e.* Marginal pyroxenite zone (MPxZ), is heterogeneous, pyroxenitic in composition (abC, baC) and is located between the rhythmic Peridotite zone and surrounding mica gneiss.

The Layered series consists of rhythmicallylayered units composed of cumulates of the olivine-clinopyroxenecrystallisation order orthopyroxene-amphibole. Most commonly the unit commences with a olivine cumulate member, which is followed by olivine-clinopyroxene cumulate and then а clinopyroxeneorthopyroxene cumulate member. More evolved cumulates, with plagioclase as the cumulus mineral, are normally lacking, and the units are thus incomplete. The units are not laterally continuous, and they cannot be connected over tens of metres from one drill hole to the other.

128 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 93. <u>a)</u> Olivine (Ol) in clinopyroxene (Cpx) – orthopyroxene cumulate of Rausenkulma. Sample 9619563, KKI/RAU-8/60.90- 61.36 m, ab(\$)C, RPrdZ3, \$ = 1.4 %, Ni = 0.06 wt.%. <u>b</u>) The sulphide mineralisation of Rausenkulma is hosted mainly by clinopyroxene (Cpx) cumulate with magmatic amphibole. Sulphides consist of pyrrhotite, pentlandite and chalcopyrite. Sample 9619572, KKI/RAU-8/140.2-140.7 m, ao\$C, RPrdZ2, \$ = 8.9 %, Ni = 0.18 wt.%. <u>c</u>) In Posionlahti the olivine cumulate with intercumulus clinopyroxene (Cpx) has serpentinised. Sample 9619696, VM/PSL-5/242.1- 242.6 m, o\$MC, DuZ2, \$ = 0.66 %, Ni = 0.18 wt.%. <u>d</u>) Magnetite/ilmenite-plagioclase cumulate of Alter do Chao. Sample 9533087, GbZ3, FeO^{TOT} = 60.2 wt.%, TiO₂ = 12.2 wt.%.



Figure 94. Subdivision of the Rausenkulma intrusion.



Figure 95. Geological map of the Rausenkulma intrusion. Modified after Grundström and Lehtonen (1995).



130 Geological Survey of Finland Bulletin 402 Pertti Lamberg

This may be partly due to tectonic movements, but most probably the structure was complicated already primarily. The contact against the Marginal pyroxenite zone is gradual and is located where the olivine becomes a cumulus mineral. The layered series is subdivided into three zones from bottom to top: a rhythmically layered Peridotite zone (RPrdZ), Pyroxenite zone (PxZ) and a Gabbro zone (GbZ). The rhythmicallylayered Peridotite zone is

characterised by an olivine orthocumulate member (oOC) at the bottom of each unit. Subsequent members are olivine-clinopyroxene cumulate (oaC and aoC) and clinopyroxene-orthopyroxene cumulate (abC and baC). The MgO_n content is higher than in other zones ranging from 16.5 to 33.8 wt. % MgO_n (Figures 97 and 98).



Figure 97. Compositions of the Rausenkulma cumulates. **a)** Al_2O_3 n versus MgO_n. **b)** In the CMA diagram, Rausenkulma samples form a pattern typical for the cumulates of crystallisation series olivine-clinopyroxene-plagioclase. **c)** Sulphides versus MgO_n indicate that the sulphide-rich samples and the mineralisation are located in the rhythmic peridotite subzone 2. **d)** Co# versus Ni#. Field with solid black line delineates the mineralised samples. A solid grey line shows the field of Stormi ore samples, and dashed the Stormi barren cumulates.



Figure 98. Variation of selected elements as a function of stratigraphic height in metres.

The rhythmical Peridotite zone consists of three subzones, which are numbered from bottom to the top (RPrdZ1-3). The subdivision is based on the composition of sulphides: Subzone 1 and 3 are depleted in chalcophile elements compared to subzone 2, as indicated by moderate Co# in the former (>10) and low in the latter.

The pyroxenite zone is more evolved than the rhythmically-layered Peridotite zone and the boundary is set to the bottom of the first rhythmic unit, which does not contain olivine as a cumulus mineral. Units commence with a clinopyroxene-orthopyroxene cumulate member, which becomes more orthopyroxene and plagioclase-rich upwards in the stratigraphy. The appearance of plagioclase as a cumulus phase marks the beginning of the Gabbro zone. The Gabbro zone is encountered only in outcrops. It is characterised by a high $Al_2O_3_n$ content (9-11 wt.%) compared to other zones. The pyroxenite zone is intermediate in chemical composition as shown in Figure 98.

A tentative stratigraphic column of the Rausenkulma intrusion based on drill hole RAU-8 and outcrop samples of the Gabbro zone is presented in Figure 98. The angle of layering cannot be measured, and the inferred thickness of the stratigraphic column, 340 meters, has to be regarded as the maximum thickness.

Rausenkulma includes a weak sulphide mineralisation (Grundström and Lehtonen 1995). This mineralisation is located in the rhythmic peridotite subzone 2 (RPrdZ2), and the mineralogy is a typical pyrrhotite-pentlandite-chalcopyrite. The host rock of the sulphide dissemination is clinopyroxene-olivine cumulate with a moderate MgO_n (22-26%), thus the host cumulate is not the most primitive one. The highest Ni and Cu content are 1.08 wt. % and 0.56 wt. %, respectively. Sulphide-bearing cumulates do not differ from barren cumulates in the volatile- and sulphide-free (*VSF*) chemistry.

The sulphide fraction of Rausenkulma is Curich compared to Stormi and Laukunkangas intrusions and the Ni# are between 50 and 65. The Co# decreases from 10 in rhythmic Peridotite subzone 1 and reaches a minimum of below 5 in rhythmic Peridotite subzone.

9.2.2 Genetic considerations and geological model

The Rausenkulma intrusion has formed as the result of replenishing magmatic system where the melt has remained sulphide-saturated up to the formation of the Gabbro zone. The crystallisation order has remained all the time olivineclinopyroxene-orthopyroxene-plagioclase (Figure 99). The parental magma does not differ notably from the SiO₂-richest melts of Stormi (DuZ3-4) and Ekojoki (DuZo, Table 21). The normative plagioclase to clinopyroxene ratio decreased slightly from rhythmic Peridotite subzone 1 to subzone 3. Contemporaneously the composition of sulphides changed from evolved (Ni# \approx 50) and slightly depleted (Co# >10) to evolved (Ni# \approx 50) and non-depleted (Co# = 4-5) and finally to primitive (Ni# = 70-80) and depleted (Co# = 10-20). The olivine displays a similar pattern in its Ni content, but the Fo content of olivine remains constant.



Figure 99. Rausenkulma samples plotted on a plagioclase projection of the basalt tetrahedron demonstrating the crystallisation order olivine-clinopyroxene.

9.3 Rörmyrberget

The Rörmyrberget mafic-ultramafic intrusion is located 14 km northeast of Vindeln, central Västerbotten, Sweden (Figure 15, Åkerman 1981, Ekström 1981, Nilsson et al. 1980, Nilsson 1985 and Ylander 1997). Rörmyrberget was selected as case study to represent subeconomic а mineralisation outside in Svecofennides outside Finland. Rörmyrberget differs from the other intrusions by its primitive character and by its metamorphic mineral totally composition (Ylander 1997).

The Swedish Geological Survey (*Sveriges Geologiska Undersökning, SGU*) discovered the Rörmyrberget nickel mineralisation in 1979. *SGU* studied the ore between 1979 and 1983 and a total of 104 holes were drilled. *Swedish State Mining Property Comission, NSG* and Outokumpu Oy continued the exploration as a joint venture project 1989-1993 (Kurki and Hattula 1983, Kinnunen et al. 1993). As a result, seven different ore bodies were discovered and evaluated, but the mineral resource was too modest to be worth further action (Table 13).

Ylander (1997) studied the internal structure of the deposit, and found at least seven rhythmic units, which consist of olivine cumulate, orthopyroxene cumulate and plagioclaseorthopyroxene cumulate. Most of the rhythmic units are incomplete and largely pyroxenitic

9.3.1 Observations

Rörmyrberget intrusion is a sill-like sheet, 1.3 km long, 50-350 meters thick and extends to a depth of at least 750 meters (Figures 100 and 101). Layering dips to the south 50-60° in the eastern part of the intrusion and 10-40° in the western part. The current mineralogy of the Rörmyrberget is metamorphic as evidenced by mineral compositions and textures. Olivine and orthopyroxene occur mainly as prismatic, elongated and non-oriented grains forming in places jackstraw texture (Nilsson 1985 and Ylander 1997). Ca-rich magnesio-hornblende and

Ca-poor magnesio-cummingtonite coexist and occur as prismatic grains, which can also be found together with phlogopite as inclusions in orthopyroxene. Mineralogy cannot be used in the interpretation of the structure and petrogenesis of the intrusion; therefore the elucidation is based solely on petrochemistry and normative mineralogy.

Rörmyrberget is rhythmically-layered, which evidenced by the alternating orthopyroxenite and peridotite layers and appearance of sulphidebearing zones. The intrusion is mainly composed of orthopyroxene cumulates, but at least two olivine cumulate layers occur in the central part of the cross-section. Sulphide enrichments are mainly localized adjacent to the olivine cumulate layers, but not necessarily within them. Laterally, the olivine cumulate changes to orthopyroxene cumulate, and the marker horizons can be identified from the sulphide abundances, nondepleted nature and primitive compositions. Chemically they are poor in incompatible elements and rich in components bound in olivine and sulphides. The chromium content is relatively high and chromite occurs as a minor cumulus mineral.

The subdivision of the Rörmyrberget intrusion is problematic due to the existence of numerous lavers, their minor differences in mineral composition and the whole-rock chemistry, and lateral variation. Here the subdivision is based on sulphide chemistry (Figures 101-103). The chemical composition of the sulphide fraction changes from a chalcophile-depleted (Co# = 5-30) unit near the contact in the cross-section to non-depleted towards the ore horizons (Co# < 5). Between the two identified ore horizons, the sulphide fraction is chalcophile-depleted. Based on this, the zoning three units were established: Upper unit (UU), Middle unit (MU) and Lower unit (LU). The upper unit consists of four members: an upper border member (UbM), upper enveloping member 1 (Ue1M), upper mineralised

134 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 100. Geological map of the Rörmyrberget intrusion. Unfilled fields indicate the outcrops. Modified after Ylander (1997). Coorinate system is Swedish National Grid.





member (UmM) and an upper enveloping member 2 (Ue2M). The middle unit (MU) has not been divided into members. The lower unit contains members similarly to the upper unit: a lower enveloping member 1 (Le1M), lower mineralised member (LmM), lower enveloping member 2 (Le2M) and a lower border member (LbM). The structure of the Rörmyrberget intrusion is symmetrical in cross-section, where the middle unit is the centre of the section. In most of the places the section is incomplete; some of the members are missing.

The Middle unit and both of the Border members are pyroxenitic in composition; mainly orthopyroxene cumulates. The normative sulphide content is low and sulphides are slightly chalcophile element -depleted as indicated by moderate Co# (Co# ~10). All four enveloping members (Ue1M, Ue2M, Le1M and Le2M) are orthopyroxene cumulates with occasional olivine cumulates. Sulphides are high in Ni# and nondepleted in chalcophile elements, thus Co# is between 5 and 10, and it decreases towards the mineralised units (Figure 103).

The mineralised members are characterized by the presence of olivine cumulates and low Co# (<5). Although the mineralised members are on average richer in MgO_n than the other units (Figures 103-105), the mineralisations and mineralised samples themselves are mainly orthopyroxene cumulates with a moderate MgO_n content between 24 and 36% (Figure 105). Very few of the olivine and olivine-sulphide cumulates contain more than 1 wt.% normative sulphides.

The definition of Rörmyrberget cumulates and stratigraphic members are based on the calculated normative content of olivine, orthopyroxene, sulphides, plagioclase and intercumulus liquid. Olivine cumulates are rich in magnesium ($MgO_n = 35.45$ %), orthopyroxene cumulates are moderate in magnesium ($MgO_n = 20.35$ %) and rich in chromium ($Cr_2O_3_n = 0.2-1.0$ %) and plagioclase-orthopyroxene cumulates are rich in aluminium ($Al_2O_3_n = 10.20$ %) as depicted in Figure 104.

All the Ni sulphide occurrences in the Rörmyrberget intrusion are relatively small, scattered, located in the Upper and Lower mineralised members and are hosted by pyroxenitic rocks (Figures 103 and 104). The average normative sulphide content of the mineralisations is 10 wt.% and Ni 0.7 wt.%. The Ni tenor is high, but Cu is low (average 12 % Ni SF and 0.8 % Cu SF). The PGE tenor is low (Figure 107). The mineralised samples are on average slightly richer in silica, chromium, vanadium, manganese, zinc and molybdenum than the corresponding barren cumulates. Although V_2O_3 n, MnO n, Mo and Zn analogous to Bruvann and Laukunkangas could refer to black schists, sampled graphite-bearing gneisses close to Rörmyrberget do not exhibit high V_2O_3 n, MnO n, Mo and Zn contents like in the cases mentioned above.

The rock textures indicate that the minerals of Rörmyrberget are metamorphic in origin. The composition of the olivines analysed varies from Fo_{76} to $Fo_{89.6}$ and the Ni content is between 250 and 3700 ppm. Both the Ni and Fo content are higher in the mineralised members than in other members (Figure 106). Compared to the tholeiite reference curve by Duke (1979), the mineralised units plot on the curve but others mainly below it. Orthopyroxene reproduces the distribution pattern olivine (Figure 106). The observed of compositions correspond to the expectations based on normative mineralogy, composition of the sulphide fraction and whole-rock composition. The compositions of analysed olivine and orthopyroxene are consistent with each other (not shown), but also with sulphides (Figure 106). This suggests that though the textures indicate metamorphic origin, the metamorphic process has been isochemical and the rock compositions – most probably – do not differ significantly from the primary igneous ones.

The average Ni# at Rörmyrberget are significantly higher than in the corresponding orogenic intrusions of Finnish Svecofennides. Generally, the Ni and Co# display a negative





138 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 104. <u>a-d</u> Al_2O_3 *n*, Cr_2O_3 *n*, normative sulphide content and Ni wt.% against MgO_n . <u>e</u>) Normative mineral composition, % of mineral indicated by plotmark, *vs.* MgO_n content of Rörmyrberget cumulates. <u>f</u>) Variation of MgO_n content in different members of Rörmyrberget illustrated in box and whisker diagram. For an explanation of the box and whisker diagram see terms and nomenclature in Chapter 20.

correlation. The sulphides with Ni# = 99 and Co# = 2.8 are interpreted most primitive in composition. The ore samples plot on the Co# versus Ni# graph along a line connecting the primitive sulphide to the origin, which refers to the mobilisation of Cu-rich sulphides. Instead, the barren cumulates distribute in a range which refers to a fractionation of olivine and sulphides with various ratios.

9.3.2 Genetic considerations

The parental magma of Rörmyrberget has been more primitive than in the Svecofennian

ultramafic intrusions in Finland (e.g. Stormi, Ekojoki). The overall high normative sulphide content proves that the parental magma of the Rörmyrberget intrusion was sulphide-saturated during emplacement. Anomalous high contents of $V_2O_3_n$, MnO_n , Mo, and Zn refer analogously to Bruvann and Laukunkangas, the presence of black schist component, and the triggering of the ore-forming process by contamination with black schist. The sampled graphite-bearing mica gneisses in the present surrounding of the intrusion are not the contaminants, since they exhibit low concentrations of the above-mentioned indicator elements.



Figure 105. Rörmyrberget: <u>a-b)</u> Co#_BM and Ni#_BM vs. MgO_n. <u>c)</u> Co# (calculated from XRF analyses from samples with cumulus sulphides) vs. Ni#_XRF. <u>d)</u> Variation of Co#_XRF content in different members of Rörmyrberget illustrated in box and whisker diagram. For an explanation of the box and whisker diagram see terms and nomenclature in Chapter 20.



Figure 106. a) Ni content of olivine versus Fo content. Curve of fractionation of olivine in sulphide undersaturation after Duke (1979) and the field of Stormi is shown for reference. b) Ni versus Mg# of orthopyroxene. Bruvann (BRU) and Laukunkangas (LAU) fields are shown as a reference and the trendline of Laukunkangas is shown as a heavy solid curve. c) Ni# versus Mg# of orthopyroxene. d) Co# vs. Ni of orthopyroxene. In all figures (a-d) the compositions of olivine and orthopyroxene are microprobe analyses.





Figure 107. Chondrite normalised compositions of sulphide fraction. Samples 9838254 and 9838255 from the Upper mineralised member, others from the Lower mineralised member.

10 BARREN INTRUSIONS

Three barren orogenic mafic-ultramafic intrusions are included in the study. Posionlahti and Porrasniemi are Svecofennian intrusions in Finland, the former is ultramafic and the latter mafic. Alter do Chão in Portugal represents a mafic intrusion from a different geological environment.

10.1 Posionlahti

The Posionlahti intrusion is located 3-4 km north of Stormi in the Vammala Ni belt (Figure 62, p 99.). It is totally ultramafic, relatively large in size and represents a Ni-depleted type. The Posionlahti intrusion was the target of Outokumpu's Ni-exploration in 1981-1982 (Pehkonen 1983) and 1987-1989 (Vesanto 1989). Mäkinen (1984, 1987) and Peltonen (1995b, c) have previously studied the Posionlahti intrusion.

The intrusion is roundish in its horizontal section, the surface area is ca. $800 \times 1000 \text{ km}^2$ and it extends to a depth of 350 m (Figure 108, Pehkonen 1983). Only the gabbroic parts of the intrusion outcrop on the small islands of lake Rautavesi. It is surrounded by mica gneisses with graphite-sulphide schist intercalations, which are also found as inclusions in the intrusion.



10.1.1 Observations

Five exploration diamond drill holes have been drilled in Posionlahti (Figure 108). All of them start from the intrusion and end in mica gneiss. thus the intersection of the intrusion is incomplete. Based on drill hole samples, which lack gabbroic rocks, Posionlahti is subdivided into two zones: the Dunite zone (DuZ), which comprises more than 90% of the intrusion and the heterogeneous Marginal pyroxenite zone (MPxZ), which occurs close to the contacts. Since the original position and bottom of the intrusion are unknown, the reference profile is based on the drill hole PSL-5, where the lower contact with mica gneiss was set to 0 m, and the structural distance was measured from that point upwards. The total length of the profile is 320 meters.

A Marginal pyroxenite zone appears at the contact between mica gneiss and the Dunite zone. It consists of orthopyroxene-clinopyroxene or orthopyroxene cumulates, and its thickness varies from 1 to 70 meters. Chemically it can be

distinguished from the Dunite zone on the basis of a lower MgO n content (MgO n < 34%).

The Dunite zone consists almost entirely of olivine (sulphide) ortho-, meso- and even adcumulates (Figure 93c, p. 128 and Figure 109). On the basis of the dominant intercumulus pyroxene (normative), the Dunite zone is divided into three subzones. Normative clinopyroxene dominates especially in the lower part of Dunite subzone 1: in subzone 2 the normative clinopyroxene disappears and normative orthopyroxene becomes practically the only intercumulus mineral, but in Dunite subzone 3 the normative clinopyroxene appears again, although not as abundant as in subzone 1. The decrease in the Cr_2O_3 *n* content from a level of 0.6-1.0 % to 0.3-0.7 marks the turn from subzones 1 and 2 to subzone 3. Due to the lack of (normative) clinopyroxene in intercumulus mineralogy the *CaO n* content is very low (<0.5 %) in subzone 2 (Figure 110a). Generally, incompatible elements display the lowest values in Dunite subzone 2.



Figure 109. Variation in selected parameters against distance from the contact against mica gneiss in drill hole PSL-5 (Figure 108).

The average normative sulphide content in Posionlahti is 1.9 wt. % and it is highest in the Marginal pyroxenite zone and Dunite subzone 3. Some thin (15 cm) sulphide-rich veins exist within Dunite subzone 3 and in the Marginal pyroxenite zone (Figure 111). Posionlahti sulphides are, however, Ni- and Cu-poor: the average Ni tenor is 1.9 wt. % and the Cu tenor 0.8 wt. %. This is reflected in the Co#, which are unusually high, compared to Ekojoki and Stormi. The Co# are with some exceptions between 18 and 40 (Figure 110c). Ni# varies only slightly from 55 to 85. In the Co# vs. Ni# plot, the Posionlahti sulphides form a quite dense cluster with a weak positive correlation (Figure 110c). In the stratigraphic profile the Co# are around 10 in the Marginal pyroxenite zone, the values increase

to 30 in Dunite subzone 1 and keep that level until the middle of subzone 2 where they rise to 35 and decrease after 60 meters back to a value of 30. Ni# increase all the way from the 65 of the Marginal pyroxenite zone to 77 in the middle of the Dunite subzone and then decrease to 65 simultaneously with the Co# as depicted in Figure 111. The *PGE tenor* of the Posionlahti is low: in two sulphide-rich samples that were analysed, the *PGE tenor* was 220 and 650 ppb.

The olivine composition of Posionlahti varies from Fo_{76.5} to Fo_{80.7} and the average Ni content, less than 200 ppm, is very low compared to the Stormi intrusion (electron microprobe analyses, Figure 110b). The *Fo* content of olivine increases towards the central part of Dunite subzone 2 and





Figure 110. <u>a)</u> CaO_n versus MgO_n shows the differences between the Dunite subzones 1-3.

b) Ni versus Fo content of olivine, Posionlahti, electron microprobe analyses. For reference the field of Stormi olivines as well as the curve showing the compositional evolution of olivine in fractional crystallisation in sulphide undersaturation (Duke 1979).

c) Co# versus Ni# of Posionlahti samples. Fields of Stormi ore samples (lower field) and Stormi barren samples are shown for reference.


Figure 111. Variation in selected parameters against distance from the contact against mica gneiss in drill hole PSL-5 (Figure 108).

decreases again in subzone 3. The chrome spinel of Dunite subzone 1 has a high Cr/(Cr+Al)(average 0.67) and the range is quite narrow compared to Stormi and Ekojoki (Figure 31). In chromite, Zn has a positive correlation with Al_2O_3 and the Zn content of Posionlahti chromite is lower than that in Ekojoki and Stormi even if compared with the Cr# of the chromite

10.1.2 Genetic considerations

The highest Fo content of olivine at Posionlahti is $Fo_{80.7}$ analysed in an olivine mesocumulate sample. Since the olivine content

is high (80 wt.%), trapped liquid shift has not been significant and Fo_{82} was selected to represent the primary magmatic olivine. Ni content of olivine is low, 250 ppm at maximum, which equals to 27 ppm Ni in silicate liquid Table 21). The *Ni tenor* is 1.75 wt.% and the Ni# and Co# of the most primitive sulphide fraction are 53.7 and 17.8, respectively. The low Ni content of the olivine, the low Ni tenor and high Co# demonstrate that the parental magma of Posionlahti has been depleted in chalcophile elements because of sulphide segregation prior to formation of the Posionlahti intrusion.

10.2 Porrasniemi

The Porrasniemi intrusion is located 30 km north of Lammi, central Finland. is It differentiated, mainly gabbroic intrusion and is barren of Ni-Cu sulphides. Lamberg (1990) previously studied the Porrasniemi intrusion. The Porrasniemi intrusion belongs to the Pori-Vammala-Mikkeli migmatite zone, characterised by intense migmatised turbiditic greywackes and crosscutting synkinematic granitoids (Kilpeläinen 1998). The metamorphic grade was already high (670 °C, 5-6 kb) at the initial stage of structural development, before the intrusion of synkinematic tonalites, and the high intensity of the hydration reactions at the retrograde stage are typical of porphyroblastic rocks in the area (Kilpeläinen 1998, Kilpeläinen et al. 1994).

10.2.1 Subdivision, chemistry and mineralogy

The Porrasniemi intrusion is a layered gabbroic sill, the structure of which can be revealed by macroscopic layering, modal rhythmic layering, microscopic layering, grain size lamination and megascopic layering, which allow the stratigraphic classification into series and zones. The intrusion consists of three blocks:

Kytö, Kärki, and Terrinen (Figure 112). They occur conformably in migmatised garnet-biotitemica gneisses, originally greywackes, and have been tilted in deformation to an almost vertical position. The stratigraphic thickness of the sill is about 520 meters. The blocks are divided into a Marginal and Layered series (Figure 113). The Marginal series is pyroxenitic and dominated by orthopyroxene; the cumulates are orthopyroxene cumulates (bC) and orthopyroxene-clinopyroxene cumulates (baC). Therefore the Marginal series is called descriptively a Marginal pyroxenite zone. It separates the Layered series from underlying gneisses. Reversal differentiation, country rock fragments and angular discordance with a layered series characterise the Marginal series.

The layered series consists of a Peridotite zone (PrdZ), Pyroxenite zone (PxZ), and a Gabbro zone (GbZ). The zones have gradual contacts. The Peridotite comprises olivinezone clinopyroxene±orthopyroxene cumulates. The appearance of olivine as the cumulus mineral and the change from orthopyroxene-dominating to clinopyroxene-dominating cumulates defines the contact between the Peridotite zone and layered Marginal zone, where the contact is gradual. The disappearance of olivine by a peritectic reaction



Figure 112. Geological map of the Porrasniemi intrusion.



and its replacement by orthopyroxene marks the boundary between the Peridotite (oa±bC) and (clinopyroxene-orthopyroxene Pyroxenite cumulate, abC) zones. Plagioclase appears as cumulus mineral in the Gabbro zone (GbZ). Its lower parts consist of clinopyroxeneorthopyroxene-plagioclase cumulate (abpC) and upper parts of plagioclase-orthopyroxene cumulate (pbC).

In chemical composition, the Peridotite zone can be recognized from its high MgO_n content (21.8-28.2 wt. %, Figure 114). In the pyroxenite zone, the MgO_n content decreases gradually to 17 wt. % MgO, and the CaO_n increases to above 10 wt. %. The appearance of plagioclase as the cumulus mineral in the Gabbro zone is reflected in the $Al_2O_3_n$ content, which jumps to 20 % (Figure 114).



Figure 114. Variation of selected variables against stratigraphic height in Porrasniemi intrusion.

Minerals and mineral textures are well preserved in Porrasniemi. Typical alteration products, serpentine+magnetite and secondary amphiboles, are present in small quantities. The Fo content of olivine (Fo₇₂₋₈₀) and the Mg# of orthopyroxene (72-81.5, Figures 115 and 116)

decrease as a function of stratigraphic height and in generally are at the same level as in the Peridotite zone of Laukunkangas. The Ni contents of olivine and orthopyroxene are significantly lower than in Laukunkangas and at about the same level as in Posionlahti, which manifests the chalcophile-depleted nature of the parental magma (Figure 115).

Sulphides comprise as an average 0.8 wt. % of samples, and they are above 0.3 wt. % in 49 of 63 samples (78 % of all samples). Weak sulphide mineralisation is located at the transition from the

pyroxenitic Marginal zone and Peridotite zone in the eastern part of the Kärki block, with a maximum of 6.6 wt. % sulphides, 0.14 wt. % Ni and 0.08 wt. % Cu. Geophysical surveys do not indicate the existence of any significant sulfide enrichment in the Marginal zone below the lake. The sulphide mineral paragenesis is pyrrhotitechalcopyrite and cobalt pentlandite. In the Co# vs. Ni# diagram, Porrasniemi shows an increasing Co# with a decreasing Ni#, similarly to other mainly gabbroic intrusions of Bruvann and Laukunkangas.



Ni# BM

Figure 115. <u>a)</u> Ni of olivine versus Fo of olivine at Porrasniemi, after microprobe analyses. For reference the field of Posionlahti (PSL) and Laukunkangas (LAU) olivines and model curve of fractionation of olivine in sulphide-undersaturation (Duke 1979) are drawn. <u>b</u>) Ni content of orthopyroxenes versus Mg#, after microprobe analyses. Field of Laukunkangas (LAU) orthopyroxenes and general evolution trend are drawn for reference. <u>c</u>) Co# versus Ni# of Porrasniemi samples. Fields of Laukunkangas ores (LAU ORE), Laukunkangas barren cumulates (LAU) and Posionlahti (PSL) are shown for reference. <u>d</u>) Porrasniemi samples plotted on plagioclase projection of the basalt tetrahedron suggesting a crystallisation order olivine-clinopyroxene-orthopyroxene.



Figure 116. Variation of the chemical composition of orthopyroxene and sulphide fraction (Ni#, Co#) as a function of stratigraphic height, in Porrasniemi. The compositions of orthopyroxene were determined with an electron microprobe.

10.2.2 Radiometric dating

The U-Pb age of the Porrasniemi intrusion was determined from zircons separated from the sample A1218 collected from the outcrop 3-PPL-88, which represents the upper part of the Gabbro zone (GbZ) in the northernmost Kytö block (Figure 112). The rock is plagioclaseorthopyroxene mesocumulate (pbC) consisting of a relatively fine-grained (1.5 mm) cumulus and orthopyroxene. plagioclase (An_{60-75}) Actinolitic amphibole and phlogopite are the main intercumulus phases, while clinopyroxene, quartz, apatite, rutile and pyrrhotite are the accessory minerals. About 20 mg of zircon was extracted by the methods described by Vaasjoki (1977) from 20 kg sample. No baddeleyite was detected.

The zircon in the sample is subhedral with occasional well-developed prism and pyramid faces and is generally less than 100 μ m in diameter. Two fractions were analysed for their lead isotopic composition and uranium and lead

concentrations using standard techniques (Vaasjoki 1977). The results (Table 23, Figure 117) demonstrate that the Porrasniemi intrusion yield an age of 1879 ± 3 Ma. As the heavier fraction A is concordant within experimental error, the age estimation must be regarded reliable. The Sm/Nd age for Porrasniemi is 1849 \pm 25 Ma (n=4, MSWD=1.0) slightly younger than the zircon age.

The published radiometric ages of the maficultramafic Svecofennian intrusions range from 1856 Ma to 1901 Ma, with an average of 1883 Ma (Peltonen 2005). Porrasniemi registers practically the same age as Hitura (1877±2 Ma, Isohanni et al. 1985), Hirsikangas (1878±17, Vaasjoki and Sakko 1988), Skåldö (1885±7, Patchett and Kouvo 1986), Hyvinkää (1880±5, Patchett and Kouvo 1986), Laukunkangas (1880±3 Ma, Huhma 1986), Kotalahti (1883±6 Ma, Gaál 1980), and Ylivieska (1883±8, Patchett and Kouvo 1986) (Peltonen 2005).

Fraction	U conc	Pb conc	²⁰⁶ Pb/ ²⁰⁴ Pb	206Pb/238U	±2 SE	²⁰⁷ Pb/ ²³⁵ U	± 2 SE	²⁰⁷ Pb/ ²⁰⁶ Pb	± 2 SE	Corr.	T _{206/238}	$T_{207/235}$	$T_{207/206}$
	(ppm)	(ppm)	(meas.)		(%)		(%)		(%)				
A. 4.3-4.5	466.6	164.2	7192	0.3374	0.65	5.348	0.65	0.1150	0.15	0.97	1874	1876	1879
B. 4.2-4.3	677.4	236.8	29588	0.3359	0.65	5.327	0.65	0.1150	0.15	0.97	1867	1873	1879

Table 23. U-Pb mineral data from the Porrasniemi intrusion (M. Vaasjoki and M. Sakko, Geological Survey of Finland).



10.2.3 Geological model

indicate Porrasniemi cumulates а crystallisation series olivine, clinopyroxene, orthopyroxene plagioclase. and Marginal pyroxenite displays a crystallisation order olivine, orthopyroxene, clinopyroxene and plagioclase, which is probably due to crustal contamination. However, major and minor element chemistry of the marginal pyroxenite does not differ from the pyroxenite zone cumulates. The presence of gneiss fragments and xenoliths in the marginal pyroxenite (fragmental unit, Lamberg 1990), remain therefore as the only evidence of the contamination.

Sulphides of the Porrasniemi intrusion exhibit quite unique compositional trends. The Co# and Ni# in the Peridotite zone correlate positively, while in the Pyroxenite zone the correlation is not

Figure 117. Concordia diagram of the Porrasniemi gabbro zircon fraction by M. Vaasjoki, Laboratory for Isotope Geology, Geological Survey of Finland.

observed (Figure 115c). The Co# is higher in the Peridotite zone and the most primitive sulphides in terms of low Co# are encountered in the pyroxenite zone (Ni# = 65.8 and Co# = 7.7). Cumulates of the Marginal pyroxenite zone display quite high and Ni# (Ni# = 60-67), but the Co# varies more widely from 10 to 22. A quite complicated model is required to explain the compositional variations observed.

According to the olivine Ni and Fo content, the first magma to enter the Porrasniemi magma chamber producing the Marginal series cumulates was, about the average level of basaltic melts in terms of Ni content (Table 21). Towards the peridotite zone, the magma developed more primitive in terms of MgO_n content, Fo content of olivine and Ni# of sulphides, but simultaneously the Co# of sulphides increased from 10-22 to values between 15 and 32 (Figure

115c). This can be explained by the fractionation of sulphides upstream.

From the centre towards the top of the Peridotite zone, the Co# and Ni# decrease reaching finally at the bottom of the Pyroxenite zone the same value as in the Marginal pyroxenite zone. In terms of sulphide composition, the trend is evidence of the change in the composition of the magma entering the Porrasniemi chamber from developed into more primitive. Thus, a large amount of sulphides had fractionated from the first magma whereas only a small amount of sulphides had fractionated from the lately emplaced melt. However, this development ends at the Peridotite zone and from the bottom of the overlying Pyroxenite zone the Ni# decreases and Co# is constant or slightly increases, indicating a fractionation of mafic silicates with or without a small amount of sulphides. Numerical modelling of the sulphide fractionation is presented in chapter 11.2.

10.3 Alter do Chão

The Alter do Chão intrusion is located in eastern Portugal, 60 kilometres west of Badajoz and some kilometres southeast of the town of Alter do Chão (Figure 15). Geologically, it is located in the Ossa Morena Zone (Dallmeyer and Martinez Garzia 1990, Mateus et al. 2005), which extends from Portugal to Spain. The Aguablanca intrusion (Tornos et al. 2001, Ortega et al. 2004) is located in the south-eastern Spanish part of the zone.

Alter do Chão represents barren intrusions in the geological environment, differing from the other cases. There are no published geological studies of Alter do Chão, but it has been the subject of nickel exploration at least in two periods. Interest arose in 1993 when the Aguablanca Ni mineralisation was discovered in Spain. Outokumpu Oy did geological mapping and sampling 1987-1999 and finally made some drill holes in 2000, but only minor iron sulphides were located in the border zone of the intrusion.

The oldest rocks of the Alter do Chão area are the upper Proterozoic schists and gneisses of sedimentary, volcanic and intrusive origin (Jokela 1988). These are overlaid by Cambrian schists, volcanic rocks, limestone and dolomites. Lower Silurian metasediments and minor metavolcanites are at the top of the stratigraphy. Various Prehercynian and Hercynian felsic-intermediate intrusive rocks cut the older volcano-sedimentary rock sequences.

The mafic-ultramafic intrusions in the area vary from dunites via peridotites to gabbroids. Intrusions are fractionated and cumulus textures are common. Some of the intrusions or parts of them display ophitic to subophitic textures. According to the structural studies of Jokela (1998), the Alter do Chão intrusion cuts the structures of the first identified deformation (D_1) . The main schistosity (S_0, S_1) of country rocks is obscured by the contact metamorphism but still weakly recognisable in some outcrops of the contact area. During the second (D_2) deformation, the entire intrusion was folded, boudinaged into three different parts, sheared and faulted. Younger, post D2 faults also modified the structure of the intrusion.

The Alter do Chão intrusion is about 15 km long and 1.5-3.5 km wide (Figure 118). The intrusion is mainly in contact with Cambrian limestone and partly in the northeast with Postcambrian syenites. Limestone in contact with the intrusion are in parts suffering from contact metamorphism. The southern contact is tectonic, but in the east and north hornfelses are encountered some tens of metres away from the intrusion. Rhythmic layering has been observed in Alter do Chão and the direction of stratigraphic top has been locally determined, but there is not a consensus on the stratigraphy and the mutual relationships of the three series.

152 Geological Survey of Finland Bulletin 402 Pertti Lamberg

10.3.1 Subdivision, mineralogy and chemistry

Alter do Chão is divided into the northwest, central and southeast blocks (Figure 118 and Figure 119). Three series can be identified: 1) ultramafic series, 2) mafic series and 3) gabbro

series. The first two series are encountered only in the south-eastern block.

The ultramafic series consists of ultramafic cumulates after the crystallisation order olivineorthopyroxene-plagioclase-clinopyroxene and it is dominated by olivine ad- and mesocumulates (Figure 120). The Al_2O_3/TiO_2 about 10 of



Figure 118. Geological map of the Alter do Chão intrusion. Modified after geological maps of Outokumpu Minera Española. Grid 2.5 km. Numbers and arrows refer to profile number, dots show sample locations.



Figure 119. Subdivision of the Alter do Chão intrusion.



ultramafics is characteristic, compared to the mafic series, where Al₂O₃/TiO₂ is 27. The most evolved cumulate of the Ultramafic series is orthopyroxene cumulate encountered only as narrow lenses. The ultramafic series is divided into Ultramafic zones 1 and 2. The difference between the zones is in MnO n content: in a given MgO n content Ultramafic zone 2 is richer in MnO n than zone 1, as shown in Figure 120. Since the rocks consist almost entirely of olivine (>70%) and there is no difference in the interpreted intercumulus mineralogy. the difference is most probably due to the higher content of Mn in olivine of the Ultramafic zone 2.

A mafic series envelops the Ultramafic series. The contact is not outcropped, but the presence of intermediate cumulates refer to gradual contact. The mafic series consists of cumulates of the olivine-clinopyroxenecrystallisation series plagioclase. Mafic zone 1 is studied by four olivine orthoand olivine-clinopyroxene cumulate samples intermediate between the Ultramafic and Mafic series and this indicates a crystallisation series olivine-clinopyroxeneorthopyroxene-plagioclase. Mafic zone 2 indicates а crystallisation order olivineclinopyroxene-plagioclase and it consists of olivine orthocumulate. olivine-clinopyroxene olivine-plagioclase cumulate and cumulate. plagioclase-clinopyroxene cumulates (oOC-oaCopC-paC).

The Gabbro series is divided into four zones. Gabbro zone 1 consists of ophitic plagioclaseclinopyroxene gabbros. The central block is dominated by Gabbro zone 1. Towards Gabbro zone 2, the amount of magnetite increase and the boundary against Gabbro zone 2 is set where the magnetite content reaches 10 vol. %. Gabbro zone 3 consists of magnetite-plagioclase (60%:30%) cumulates (Figure 93d, p. 128). It is a layer of some metres thick in the NW block, but due to its diagnostic composition, it deserves to be named as a zone. North of the Gabbro zone 3 there are ophitic gabbros, which resemble in mineralogy and chemical composition the rocks of Gabbro zone 1. They are, however, called Gabbro zone 4, since the mutual positions of zones 2 and 3 indicate that the stratigraphic top is towards north, and therefore these gabbros must be stratigraphically above the magnetite-gabbros of zone 3.

The mutual relationships between the series are not well established. The intrusion in the south-eastern block appears to be zoned and the most primitive rocks are located in the central part of the intrusion. The Ultramafic series forms the core of the SE block and is surrounded by the Mafic series, which is then enveloped by the Gabbro series (Figure 118). There are some outcrops where ophitic gabbro of Gabbro zone 1 intersects the olivine cumulate of the Ultramafic series. In some outcrops, however, rhythmic lavering relates that the stratigraphic top is directed from the margin of the Mafic series towards the centre of the intrusion. The contact between the Ultramafic and Mafic series cumulates and the Gabbro series ophitic rocks is usually strongly tectonised. Structures are relatively steeply dipping in the SE block, but the magnetite-plagioclase cumulate in the NW block dips ca. 30 °to NE.

Since there are contradictory observations on the stratigraphic relationships of the rock types, a stratigraphic succession of the intrusion has not been established. Instead, a representative profile is presented in Figure 121.

Alter do Chão samples are poor in sulphides and nickel. The maximum concentration of sulphides is 1.3 wt.% and Ni 0.323 wt.%.

10.3.2 Petrogenetic considerations and geological model

Alter do Chão is a zonal intrusion, where the most primitive rocks are located in the central part of the intrusion. The Ultramafic and Mafic series display dramatic differences in the crystallisation order as depected in the CMA diagram in Figure 122. In the Ultramafic series, the order is olivine, orthopyroxene and plagioclase, and clinopyroxene is practically absent. In the Mafic series, clinopyroxene is a



Figure 121. Variation of selected elements in profile 12.



Figure 122. CMA diagram of Alter do Chão illustrating the differences in the chemical composition of the Ultramafic series (UmZ1 and UmZ2), Mafic series (MaZ1 and MaZ2) and Gabbro series (GbZ1-GbZ4).

characteristic mineral and the crystallisation order olivine-clinopyroxenechanges from orthopyroxene in Mafic zone 1 to olivineclinopyroxene-plagioclase in Mafic zone 2. This is the same as the crystallisation order of the Gabbro series with the extension to crystallisation of magnetite after plagioclase. There are at least two possible explanations for the difference between the Ultramafic and Mafic series: 1) the two rock series formed from two different magmas, 2) or contamination by limestone caused the difference observed. The sharp contacts between the Ultramafic series and Gabbro series, crosscutting relationships and considerable difference in the crystallisation order speak for the first explanation. However, the Mafic series and the Gabbro series could have crystallised from the same type of magma, since the crystallisation paths of the inferred parental magmas are equal Alter do Chão is enveloped by limestone and the intrusion is surrounded by a ca. 100 m thick hornfels shell. An assimilation of dolomitic and calcitic limestone could have increased the CaO concentration of the magma, and it is at least compositionally possible that one parental magma has produced two different series of cumulates: one without contamination (the core) and another with contamination (marginal parts). The average Al₂O₃/TiO₂ of the Ultramafic series is 10 and commonly between 8 and 12. The ratio is also the same in Mafic zone 1, but in Mafic zone 2 the Al₂O₃/TiO₂ jumps to 25. Al₂O₃/TiO₂ of limestone is 30 and hornfelses 25. Since there are two mineralogically and geochemically different rock groups and intermediate samples are rare, it is more probable that the rock series inherited from two different magmatic systems giving way to 1) rocks of the Ultramafic series and 2) rocks of the Mafic and Gabbros series (Table 21).

Alter do Chão is relatively primitive, large and non-depleted with respect to chalcophile elements. Magma has interacted strongly with the surrounding limestone. Thus some of the requirements of the Ni sulphide formation are fulfilled. What is lacking, however, is sulphur. Although sulphur-bearing bituminous shales exist lower in the stratigraphy and the intruded magma has possibly intersected them, the immediate surrounding of the intrusive body is poor in sulphur and sulphides are rare in the Alter do Chão cumulates. The highest normative sulphide abundances (0.5-1.3 %, n=6) are encountered in Gabbro zones 1 and 2. Sulphides are poor in base metals and either depleted or evolved (Figure 123c), which implies that they have not interacted with the large amount of magma and cannot be regarded as typical magmatic sulphides. The olivine and clinopyroxene analyses of Alter do Chão display a smooth trend in the nickel vs. forsterite diagram consistent with the model of olivine crystallisation in sulphide undersaturation by Duke (1979) (Figures 123a and b).



Figure 123. <u>a)</u> Ni vs. Fo of olivine, <u>b)</u> Ni vs. Mg# of clinopyroxene; both are microprobe analyses. <u>c)</u> Alter do Chão samples containing cumulus sulphides plotted on a Co# versus Ni# diagram. Stormi, Posionlahti and Porrasniemi fields are drawn for reference. <u>d)</u> All Alter do Chão samples in Co#_XRF vs. MgO_n% diagram, fields of Posionlahti, Stormi and Laukunkangas are drawn for reference.

11 CO#-NI# SYSTEMATICS IN STUDIED MAFIC-ULTRAMAFIC INTRUSIONS

11.1 Examination of Co# as a tool of sulphide segregation

11.1.1 Reliability of assays

The estimation of the reliability of the Co# in chapter 4.5.2. concluded that when the normative sulphide content of the sample is higher than 0.3 %, the Co# calculated from the bromine-methanol assays can be used as an accurate estimate of the base metal depletion. In the majority of the

targets, Bruvann, Ekojoki, Laukunkangas, Posionlahti and Stormi, the Co# increases as the sulphide content decreases (Figure 124 and Figure 125), which raises the question whether this comes from the poor accuracy of the Co analyses, i.e. systematically too high Co assays, in the low Co concentration.



Figure 124. Correlation between Co#_BM and normative sulphide content in the case study intrusions, <u>a</u>) Bruvann, <u>b</u>) Ekojoki, <u>c</u>) Laukunkangas, <u>d</u>) Porrasniemi, <u>e</u>) Posionlahti and <u>f</u>) Rausenkulma. Continues in the next figure. Notice that the scale for y axis and x axis is the same in all the figures. Lines Co#_BM=10 and Sulphides=0.3% are drawn for reference.



Figure 125. Correlation between Co#_BM and normative sulphide content in the case study intrusions <u>a</u>) Rörmyrberget and <u>b</u>) Stormi. Continues from the previous figure. Notice that the scale for y axis and x axis is the same in all the figures. Lines Co#_BM=10 and Sulphides=0.3% are drawn for reference.



Figure 126. Correlation between Co#_BM and cobalt content of the sample analysed with bromine-methanol dissolution and AAS in <u>a)</u> Bruvann and <u>b)</u> Ekojoki. Continues in the next figure. Notice that the scale for y axis and x axis is the same in all the figures. Lines Co#_BM=10 and Co_BM=0.005 wt.% are drawn for reference. Only samples with cumulus sulphides (normative sulphide >0.3%) are drawn.

Figures 126 and 127 show the correlations between the Co# and analysed cobalt content. The Co# increases as Co decreases in Bruvann, Ekojoki and Stormi, but the relationship is the opposite in Porrasniemi. Laukunkangas, Posionlahti, Rörmyrberget, and Rausenkulma show no clear relationship at all. In Laukunkangas the Co# is low (<10) in Norite

subzone 4 with low cobalt contents, whereas in Norite subzones 5-8 the Co# is high (>10) with equally low cobalt contents.

The lack of correlation between the Co# and Co content of the samples rules out the possibility that the observed relationship between the Co# and the sulphide content is the result of systematic errors in base metal analyses.



Figure 127. Correlation between Co#_BM and cobalt content of the sample analysed with bromine-methanol dissolution and AAS in <u>a)</u> Laukunkangas, <u>b)</u> Porrasneimi, <u>c)</u> Posionlahti, <u>d)</u> Rausenkulma, <u>e)</u> Rörmyrberget and <u>f)</u> Stormi. Continues from the previous figure. Notice that the scale for y axis and x axis is the same in all the figures. Lines Co#_BM=10 and Co_BM=0.005 wt.% are drawn for reference. Only samples with cumulus sulphides (normative sulphide >0.3%) are drawn.

11.1.2 Resetting of Co# and Ni# in subsolidus stages

The intrusions we studied have been subject to a long tectonometamorphic history, and the primary magmatic minerals have altered. recrystallised and re-equilibrated in the subsolidus stages. In Rörmyrberget the silicate mineralogy is totally metamorphic. In Laukunkangas and Stormi copper rich veinlets are found in association with the ores and even within the country rock, which is evidence of metamorphic sulphide remobilisation. Is it reasonable to expect that the Co# and Ni# reflect primary igneous processes?

The partition of Ni and Fe between olivine and sulphides can be determined from olivine analyses and from the composition of the sulphide fraction. The exchange partition coefficient, K_D, of Fe and Ni between the sulphide fraction and mafic silicates (Equation 7 on p. 24) varies in the intrusions between 10 and 30, with the average being 15-20 (Figure 128a, Table 24). In most of the studied intrusions, the K_D increases along with a decreasing sulphide content with the exception of Bruvann and Laukunkangas (Figure 128b). In Ekojoki the increase in K_D with decreasing sulphide content is strong and the range of K_D is the widest (Figure 128c). If Ekojoki is excluded, the average K_D of the intrusions correlates with the metamorphic grade, being highest in Rörmyrberget and lowest in Porrasniemi and Bruvann.

In the $K_D vs$. Ni tenor diagram, the different intrusions are plotted along distinct lines (Figure 128d). Brenan and Caciagli (2000) and Naldrett (2004) considered that the $K_D vs$. Ni tenor reflects the fO_2 at the temperature at which the exchange reaction between sulphide and olivine became blocked. Accordingly, the fO_2 had been high in Rörmyrberget, about the same range as in Jinchuan (Naldrett 2004), moderate in fertile intrusions and much lower in barren Porrasniemi and Posionlahti (Figure 128d). This conclusion is not supported by any other observations and the use of K_D and Ni tenor in determining the blocking fO_2 of studied intrusions is questionable.

Orthopyroxene and clinopyroxene also show good Ni-Fe equilibrium with sulphides (Figure 129). The K_D of Ni and Fe between orthopyroxene and the sulphide fraction is very high, between 40 and 60, whereas that between clinopyroxene and sulphides is closer to olivine, ranging from 22 to 34 (Table 24).

The experimentally determined K_D values for Ni partitioning between sulphide and olivine are commonly between 20 and 30 whereas the values analysed from Ni sulphide deposits are lower, mainly below 20 (Figure 130 and references therein). The highest natural values are reported in Perseverance (23 ± 4) and Renzy Lake (21.6 ± 3.4) that were metamorphosed to upper amphibolite facies, and Naldrett (1989) suggested that they represent metamorphic equilibration.

The compositions and Fe-Ni equilibria of sulphides and mafic silicates indicate that their compositions have changed in metamorphism. Since the K_D increased (Equation 7), the nickel content of the sulphide fraction increased and that of olivine decreased.

The increase in the Ni content of the sulphide fraction caused by the metamorphic increase in K_D decreases the Co# if Cu and Co remain unchanged. If the metamorphic re-equilibration caused the increase in Co#, then K_{D(Co-Fe)} between sulphide and silicate melts was higher than that of Ni-Fe. There are very few published K_D values for Co and there is no data on the change of K_D Co-Fe partition coefficient in metamorphism. Rajamani (1976) studied the distribution of Fe, Co and Ni between synthetic sulphide and orthopyroxene and observed that the K_D of Ni-Fe is about twice that of Co-Fe. If the observed increase in Co# parallel with a decrease in sulphide content is the result of metamorphism, the effect should be strongest in Rörmyrberget and weakest in Alter do Chão, Bruvann and Porrasniemi. It should also accompany an increase in the Ni# due to the increase in the K_D of Ni. Since Rörmyrberget does not show such a relationship, and because the decrease in the

162 Geological Survey of Finland Bulletin 402 Pertti Lamberg

sulphide content and increase in the Co# is accompanied by an increase in the Ni# only in Posionlahti, the conclusion is that although sulphides and mafic silicates have re-equilibrated in metamorphism and their composition has changed, the Co# and Ni# do not seem to be affected significantly, and the major features originate from the magmatic stages. The Co# vs. Ni content of olivine observed in the intrusions follows the modelled curve of sulphide-olivine fractionation, which confirms this conclusion (Figure 131).



Figure 128. <u>a)</u> Ni/Fe of the sulphide fraction vs. Ni/Fe of olivine, both in mole proportions, only samples with cumulus sulphides are drawn. Lines $K_D=10$, 20 and 30 drawn for reference. <u>b)</u> $K_D vs.$ normative sulphide content of the samples. All other targets apart from Bruvann show a clear negative correlation between K_D and sulphide content. Fitted lines of Stormi, Ekojoki and Porrasniemi. <u>c)</u> Box and whisker diagram showing variation in $K_{D(Ni-Fe)}^{Sulphide-Olivine}$ for barren cumulates with cumulus sulphides. <u>d)</u> $K_{D(Ni-Fe)}^{Sulphide-Olivine} vs.$ nickel tenor contoured with respect to fO_2 after Brenan and Caciagli 2000.



Figure 129. Ni/Fe in sulphide vs. **a)** Ni/Fe in orthopyroxene and **b)** Ni/Fe in clinopyroxene (atomic ratios). Only samples with cumulus sulphides are drawn. Best fit linear lines with equations shown.



Figure 130. Box and whisker diagram showing the variation of the K_D values between sulphide and olivine in the experimental studies and from the natural datal. Data from Rajamani and Naldrett (1978), Boctor (1981, 1982), Binns and Groves (1976), Fleet and MacRae (1987 and 1988), Naldrett (2004), Thompson and Barnes (1984), Fleet et al. (1977, 1981) and Naldrett (1989).



Figure 131. Co# vs. Ni content of olivine analysed by electron microprobe from barren samples with cumulus sulphides. Line shows the modelled relationship in case C with SCS>5. Compare to Figure 11b.

Table 24. Observed distribution coefficients of nickel (D_{Ni}) between coexisting minerals and olivine, and Ni-Fe exch	lange
partition coefficients between sulphides and mafic silicates in the case study intrusions, calculated from electron microp	orobe
analyses using trace conditions. Values in brackets are based on less than 10 observations or regression is poor.	

	D _{Ni} betv	olivine	$K_{D_{(Ni-}}^{Sulfie}$	de-mafic_s _{Fe)}	silicate	Metal ratios in sulphide fraction			
Case	Opx	Срх	Amp	Sulph	Ol	Opx	Cpx	Ni/Cu	Ni/Co
Alter do Chão	(0.240)	0.145	-	74.9	(29.4)	-	(43.2)	1.62	1.24
Bruvann	0.203	0.111	0.312	62.0	14.9	39.9	34.1	3.17	4.85
Ekojoki	0.191	0.130	0.292	(71.7)	(16.9)	(77.4)	(28.7)	1.57	9.01
Laukunkangas	0.207	(0.138)	0.315	(51.6)	17.8	59.1	31.8	2.43	(8.00)
Porrasniemi	0.217	0.137	0.322	54.7	16.3	49.1	25.9	1.66	2.72
Posionlahti	0.236	(0.172)	0.284	76.7	16.2	48.1	(23.2)	2.51	1.88
Rausenkulma	(0.236)	0.112	0.324	53.9	(18.5)	(56.1)	22.4	1.44	3.85
Rörmyrberget	0.177	0.009	0.261	86.7	19.8	60.7	(26.3)	11.76	9.43
Stormi	0.189	0.132	0.297	61.2	16.7	51.0	23.2	1.49	12.66

11.2 Sulphide segregation

11.2.1 Initial Co#-Ni# and sulphide segregation trends in the case study intrusions

On the basis of the Ni# and Co# relationships of the intrusion it should be possible, in principle, to quantify the total amount of segregated sulphides and the ratio of sulphide to olivine. Accordingly, it should be possible to estimate whether the process has been batch or fractional segregation. The increase in Co# caused by sulphide segregation should be continuous in the fractional case and sudden in batch segregation. For the numerical modelling of the sulphide segregation the initial Ni# and Co# values and the Co# vs. Ni# trend are needed. The determination, however, may be difficult especially if an intrusion shows the sulphide mobilisation Co# vs. Ni trend, i.e. the trend towards origin. The method described in Table 25 and illustrated in Figure 132a-b was found to be the best to solve the problem; the human effect is eliminated, determinations are always made in the same way and the procedure can be automated.

The initial and closing values and the fractionation trends of the case study intrusions are shown in Figure 132c. The Co#initial is at highest, >10, in depleted Porrasniemi and Posionlahti, and in Rausenkulma where it is about 8. The lowest value is in Rörmyrberget, 1.4, and in the rest of the intrusions the Co#_{initial} is between 2.7 and 3.1. The slopes of the segregation trend allow the classification of targets in two groups. Mafic intrusions, Bruvann, Laukunkangas and Porrasniemi. and ultramafic Rörmyrberget display a negative slope between the Co# and the Ni#, whereas the Co# vs. Ni# trends of the other ultramafic intrusions. Ekojoki, Stormi. Rausenkulma and Posionlahti, have a positive slope.

Table 25. The procedure used to determine the initial Ni#-Co# and the segregation trend.

Plot the barren samples with cumulus sulphides, i.e. samples with Ni<0.5 wt.%, Cu<0.5 wt.% and normative sulphides >0.3 %, in Ni tenor vs. Cu tenor diagram and calculate the Ni/Cu ratio with the best fit though the origin (Figure 132a).

²⁾ From the average Ni/Cu calculate the initial Ni#. This procedure gives more weight to high Ni and Cu tenors and less weight to low tenors that represent the base metal depleted samples.

³⁾ Plot the barren samples with cumulus sulphides in Co# vs. Ni# diagram and determine the initial Co# at or close to the initial Ni#.

⁴⁾ Eliminate the samples with a lower Co# than the initial Co#.

⁵⁾ Determine the segregation trend using the best linear fit through the initial Co#-Ni# value. The parameters Ni#_{initial}, Co#_{initial}, Co#_{initial}, Co#_{initial}, and Ni#_{closing} are needed for the modelling; the ΔCo# is used for information.





11.2.2 Quantitative models

A numerical model of the sulphide segregation in a closed system is based on the initial Ni#-Co#, the Ni#-Co# trend of the segregation, Δ Co# and composition of olivine as well as on the Mg#_{initial} and Mg#_{closing} calculated for each intrusion.

The numerical modelling of the segregation process requires knowledge on the composition of the parental magma (Table 21) and partition coefficients. For the sake of simplicity only Ni, Cu, Co and Fe/Mg were modelled. The Ni content of the parental magma was calculated using the highest Ni content of olivine and a value of 10 for the distribution coefficient $D_{Ni}^{olivine-liquid}$. The cobalt content of the parental magma was



Figure 132. a) Ni tenor vs. Cu tenor of the targets.

b) The initial Ni# is calculated from the best-fit Ni/Cu ratio, e.g. for Ekojoki Ni/Cu = 1.58 and Ni#_{initial} = 60.6. The Co#_{initial} is determined as described in Table 25. The trend is determined by the best linear fit through the initial Ni#-Co# excluding samples where Co#<Co#_{initial}. The closing values are read where the fitted line intersects the Co#_{maximum}.

c) Initial compositions shown as symbols and Co#-Ni# segregation trends as determined from barren cumulates. Exact initial and closing values are given in Tables 26-30.

calculated from the Ni content using equation 13,

$$Co_{\text{silicate liquid}} = 11.24 * \text{Ln}(\text{Ni}_{\text{silicate liquid}}) - 3.7$$

(Equation 13),

which was taken from the relationship between Ni and Co observed in basaltic volcanic rocks from the GeoRoc database (http://georoc.mpch-mainz.gwdg.de).

The partition coefficient of Ni between sulphide melt and silicate melt was calculated from the Ni content of the melt and the average Ni tenor observed in the ore or, in the barren intrusions, in samples with cumulus sulphides. Either the Cu content of the parental magma or D_{Cu} had to be fixed and $D_{Cu}^{sulphide melt-silicate melt}$ was chosen. Because Stormi, Ekojoki, Posionlahti and Rausenkulma have a positive Co# vs. Ni# slope, D_{Cu} has to be greater than D_{Ni} . The average of the D_{Cu}/D_{Ni} in the studies from natural volcanic rocks is 2.0, as shown in Figure 7, which was taken to be constant. The Cu content of the magma and $D_{Co}^{sulphide melt-silicate melt}$ was solved to fulfil the initial Ni# and Co#. In Posionlahti the technique resulted in an anomalously high $D_{Co} = 325$, and so the Co content of the parental magma was estimated on the basis of the Stormi model and equation 13 was not utilised.

The segregation of sulphides in batch and fractional segregation cases were modelled. In the former case the R-factor and in the latter case the sulphide to olivine ratio, *SCS*, and the amount of segregated sulphides (*SS*) were solved to fulfil the $Co\#_{closing}$, Ni $\#_{closing}$ in the first fractional model entitled Fract. 1, and $Co\#_{closing}$ and olivines $Mg\#_{closing}$ in the second fractional model, Fract. 2. The Excel Solver programme was used in finding the best solution in such a multivariate problem. The results are given in Table 26-Table 30.

In the fertile mafic intrusions, Bruvann and Laukunkangas, the wide and full range in the Co# and the general negative Co# vs. Ni# slope indicates that sulphides have co-segregated with olivine and the process has been fractional rather than batch segregation. According to the modelling the SCS, the proportion of sulphides of segregated phases, is 1.5-2% in Bruvann and 2-3% in Laukunkangas (Table 26). The total amount of sulphides segregated, SS, to produce the observed $\Delta Co\#$ is 0.3-0.4% in Bruvann and 0.6-0.7% in Laukunkangas. The scattering of the values, sudden reversals and jumps indicate that the process has not been closed and besides general fractional segregation there may also have been batch segregation sub-processes.

In subeconomic and ultramafic Ekojoki and Rausenkulma intrusions, the positive slope and continuous trend in Co# vs. Ni# indicates fractional segregation in a higher proportion of sulphides than in Bruvann and Laukunkangas. The modelled *SCS* is 4-5% (*Fract. 1*, Table 27). This gives a steeper Co# vs. Mg# of olivine than observed (Figure 134) whereas the model, which explains the compositional trend of olivine, has a

	Bru	vann					Laukunkangas							
		Initial		Closing	Closing, models				Initial		Closing	Closing, models		
	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2
Ni	395	134	5.3		7	1	1	329	140	4.6		8	1	1
Cu	790	22	1.7		0	0	1	659	29	1.9		0	0	0
Co	42	47	0.20		47	21	19	44	48	0.21		48	19	21
Ni#			75.3	61.6	92	62	42			70.5	47.9	90	48	72
Co#			2.7	53.4	40	53	53			3.1	60.9	40	61	61
Ol Ni ppm		1330		339	70	12	7		1383		778	84	8	13
Opx Ni ppm		405		15	21	4	2		329		10	20	2	3
Ol Mg#		87.9		74.4	87.9	77.7	74.4	ĺ	77.0		68.4	77.0	64.6	68.4
SCS			1.9*			1.9	1.5			2.5*			2.1	3.1
SS					2.9	0.5	0.4					3.0	0.6	0.7
R factor					34							32		
F%					97.1	75.3	70.4					97.0	72.0	78.0

Table 26. Bruvann and Laukunkangas models.

Obs. = observed; Ol=Olivine; Opx=orthopyroxene; SCS=100*sulphide/(sulphide+olivine) in the segregated material; SS=total amount of sulphides segregated vs. initial melt =100;F%=melt remaining, inital =100. Fract. 1= fractional segregation model, the difference between observed and modelled in Ni# and Co# is minimized; Fract. 2 = fractional segregation model, the difference between observed and modelled in Co# and Mg# of olivine is minimized. *Average sulphide content of barren cumulates.



Figure 133. **a)** Bruvann and **b)** Laukunkangas samples with cumulus sulphides in Co# vs. Ni# diagram with three models (): batch segregation of sulphides (Batch), fractional segregation of sulphides and olivine in ratios to explain the closing Co# and Ni# (Fract. 1) and fractional segregation of sulphides and olivine to explain the closing Co# and Mg# of olivine (Fract. 2). **c)** Barren samples with cumulus sulphides of Bruvann in Co# vs. Mg# of olivine of, and **b)** of Laukunkangas in Co# vs. Mg# of orthopyroxene.

negative slope in Co# vs. Ni# (Fract. 2, Figure 134). The total amount of segregated sulphides, SS, is 0.3 % in both Ekojoki and Rausenkulma, which is about half of that estimated for Laukunkangas. The samples with a lower Co# than the initial and pointing towards Co#-Ni# origin were formed by the mobilisation of the Cu rich sulphides from the initial material.

The subeconomic Rörmyrberget shows continuous Co# vs. Ni# with a negative slope (Figure 135b). The modelled SCS of about 1 is

still lower than in Ekojoki and Rausenkulma (Table 28). The analysed compositions of sulphides, olivine and orthopyroxene are in moderate agreement with the modelled ones; e.g. fractional segregation models give 48-61 ppm for the closing orthopyroxene while the lowest content analysed is 23 ppm. Stormi displays a strong sulphide mobilisation trend in Co# vs. Ni# (Figure 135a). The sulphide fractionation trend also has a positive slope, but it is steeper, relatively well continuous and defined.

168 Geological Survey of Finland Bulletin 402 Pertti Lamberg

	Eko	joki					Rausenkulma							
		Initial		Closing	Closing, models			Initial			Closing	Closing, models		3
	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2
Ni	436	147	6.4		38	27	8	318	96	3.1		32	18	4
Cu	872	48	4.2		7	5	10	636	41	2.6		8	5	8
Co	72	49	0.35		49	36	27	126	40	0.51		40	23	16
Ni#			60.6	72.2	73	72	29			54.3	66.0	67	66	19
Co#			3.2	13.6	13	14	14			8.3	25.5	25	25	25
Ol Ni ppm		1465		721	381	271	82		961		186	317	175	36
Opx Ni ppm		288		132	75	53	16		145		53	48	26	5
Ol Mg#		81.9		74.4	81.9	80.3	74.4		78.9		69.7	78.9	77.2	69.7
SCS			1.3*			4.1	0.9			1.5*			5.3	1.1
SS					0.6	0.3	0.2					0.6	0.3	0.3
R factor					157							159		
F%					99.4	93.8	80.0					99.4	93.5	76.9

Table 27. Ekojoki and Rausenkulma models. See explanations in Table 29.

Table 28. Stormi and Rörmyrberget models. See explanations in Table 29.

	Storr	ni					Rörmyrberget							
		Initial		Closing	Closing, models			Initial			Closing	Closing, models		ls
	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2	D	ppm	Sulph.%	ppm	Batch	Fract.1	Fract.2
Ni	428	150	6.4		28	23	4	241	370	8.9		55	26	20
Cu	856	41	3.5		4	3	7	481	15	0.7		1	5	6
Co	61	49	0.30		49	36	24	21	66	0.14		66	40	38
Ni#			64.4	81.3	77	81	21			92.7	73.6	96	74	63
Co#			2.9	15.3	16	15	15			1.4	9.1	9	9	9
Ol Ni ppm		1493		491	277	234	40		3673		253	546	254	202
Opx Ni ppm		336		73	62	52	9		885		23	131	61	48
Ol Mg#		83.9		73.4	83.9	82.6	73.4		89.6		80.4	89.6	82.1	80.4
SCS			1.6*			6.0	0.8			1.5*			1.3	0.9
SS					1.0	0.3	0.2					2.1	0.3	0.2
R factor					102							48		
F%					99.0	94.7	74.7					97.9	80.0	77.0

Table 29. Posionlahti models.

	Posi	ionlah	ti					Stormi -> Posionlahti						
		Initia	1	Closing	Closing, models				Initial		Closing	Closing, models		3
	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2	D	ppm	Sulph.%	ppm	Batch	Fract.1	Fract.2
Ni	432	45	1.9		25	18	11	428	150	6.4		20	10	11
Cu	864	9	0.8		3	3	6	856	41	3.5		3	2	2
Co	98	85	0.83		85	69	62	61	49	0.30		49	31	31
Ni#			71.6	73.4	78	73	50			64.4	71.6	79	72	74
Co#			23.5	39.1	38	39	39			2.9	23.5	22	23	24
Ol Ni ppm		448		109	249	180	110		1493		449	197	102	107
Opx Ni ppm		50		5	28	20	12		336		50	44	23	24
Ol Mg#		80.7		77.2	80.7	79.7	77.2		83.9		80.7	83.9	80.3	80.7
SCS			1.8*			2.7	0.6						2.9	3.2
SS					0.2	0.1	0.1					1.4	0.3	0.4
R factor					541							72		
F%					99.8	95.7	88.4					98.6	88.1	89.0

Obs. = observed; Ol=Olivine; Opx=orthopyroxene; SCS=100*sulphide/(sulphide+olivine) in the segregated material; SS=total amount of sulphides segregated vs. initial melt =100;F%=melt remaining, initial =100. Fract. 1= fractional segregation model, the difference between observed and modelled in Ni# and Co# is minimized; Fract. 2 = fractional segregation model, the difference between observed and modelled in Co# and Mg# of olivine is minimized. *Average sulphide content of barren cumulates.

which indicates that the process has been fractional. The model gives the highest sulphide content recorded in the case study intrusions, SCS = 6% (Fract. 1, Table 28). According to the model, the observed increase in Co# should take place in a very narrow forsterite content, which is not the case according to analyses (Figure 135c). The best model to explain the composition of closing olivine would change the slope of the trend in Co# vs. Ni# (Fract. 2, Figure 135a and c).

For the barren intrusions, Posionlahti and Porrasniemi, two different cases were considered: models which intend to explain the observed features within the intrusion and models to explain the formation of the depleted initial. In both Posionlahti and Porrasniemi the Co# vs. Ni# trend within the intrusion can be best explained by fractional segregation of sulphides and olivine in proportions so that SCS is 2.6-2.7% (Figure 136, Table 29 and Table 30). If the initial compositions for the non-depleted Posionlahti and Porrasniemi were equal to that of Stormi and Laukunkangas, respectively, the paths to the observed depleted initial could be achieved by the removal of 0.2-0.3% sulphides with the SCS 2.1-2.9% (Figure 136, Table 29 and Table 30).



Figure 134. **a)** Ekojoki and **b)** Rausenkulma samples with cumulus sulphides in Co# vs. Ni# diagram according to three models (): batch segregation of sulphides (Batch), fractional segregation of sulphides and olivine in ratios to explain the closing Co# and Ni# (Fract. 1) and fractional segregation of sulphides and olivine to explain the closing Co# and Mg# of olivine (Fract. 2). **c)** Barren samples with cumulus sulphides in Co# vs. Mg# of olivine of Ekojoki and **d)** Rausenkulma.

170 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 135. Sulphide and olivine compositions, observed vs. models (Table 28). <u>a)</u> Stormi and <u>b)</u> Rörmyrberget samples with cumulus sulphides in Co# vs. Ni# diagram according to three models: batch segregation of sulphides (Batch), fractional segregation of sulphides and olivine in ratios to explain the closing Co# and Ni# (Fract. 1) and fractional segregation of sulphides and olivine to explain the closing Co# and Mg# of olivine (Fract. 2). <u>c)</u> Barren samples with cumulus sulphides in Co# vs. Mg# of olivine of Stormi and <u>d)</u> Co# vs. Mg# of orthopyroxene of Rörmyrberget.

11.3 Discussion

The observed Co# vs. Ni# can be best explained as a product of the fractional segregation of sulphides with olivine, and in Laukunkangas, Porrasniemi, Bruvann and Rörmyrberget also combined with orthopyroxene. In the models the proportion of sulphides in segregated phases, *SCS*, has been highest in Stormi at 6% and lowest in Rörmyrberget at 1.3%. The estimated *SCS* equals the average normative sulphide content of barren cumulates in Bruvann and Laukunkangas, but in Stormi, Rausenkulma and Ekojoki it is significantly higher (Figure 137a). The modelled total amount of fractionated sulphides, *SS*, has been highest in the fertile intrusions and correlates between the average normative sulphide content of barren cumulates. This indicates that Co# *vs*. Ni#



Figure 136. Sulphide and olivine compositions, observed vs. models (Table 29 and Table 30), barren intrusions. a) Posionlahti and b) Porrasniemi samples with cumulus sulphides in Co# vs. Ni# diagram according to three models: batch segregation of sulphides (Batch), fractional segregation of sulphides and olivine in ratios to explain the closing Co# and Ni# (Fract. 1) and fractional segregation of sulphides and olivine to explain the closing Co# and Mg# of olivine (Fract. 2). c) Barren samples with cumulus sulphides in Co# vs. Mg# of orthopyroxene of Rörmyrberget.

systematic has potential for discriminating between barren and fertile intrusions.

The nickel content of olivine and Co# which, according to modelling, should have a linear correlation, deviate in the high Co# end at least in Bruvann, Ekojoki and Stormi: the Ni content of olivine is not as low as the Co# forecasts (Figure 131, p. 163). The reason for the observed discrepancy is neither the analyses nor the Ni-Fe-Co re-setting in metamorphism as discussed in chapter 11.1.

The feature remains unsolved, but as the compositions of olivine and sulphides follow each other, as predicted by the magmatic sulphide segregation models, the Co# and Ni# are used below for the discrimination of barren and fertile intrusions. Although this method may not be as reliable as the use of olivine analyses with trace conditions, the method has the following advantages, which makes it practicable in exploration: 1) the Ni# and Co# are based on Ni, Cu and Co analyses which are generally available

172 Geological Survey of Finland Bulletin 402 Pertti Lamberg

in all the exploration areas and targets, 2) mafic silicates are often totally altered, and olivine in particular is frequently serpentinised, 3) mineral analyses are more expensive and time-demanding than simple Ni, Cu and Co assays, 4) the interpretation of Ni *vs.* Mg# of mafic silicates is not as easy as that of Co# *vs.* Ni#. The fractionation of olivine in sulphide

undersaturation produces a decreasing trend in Ni of olivine *vs.* Mg# diagram of olivine and the slope is steeper in sulphide-saturated cases, whereas the Co# will change only slightly in sulphide undersaturation fractionation and the segregation of sulphides increases the Co# significantly.

	Porr	asnier	ni					Laukunkangas^ -> Porrasniemi						
		Initia	1	Closing	Closing, models			Initial			Closing	Closing, models		5
	D	ppm	Sulph.%	Obs.	Batch	Fract.1	Fract.2	D	ppm	Sulph.%	ppm	Batch	Fract.1	Fract.2
Ni	288	53	1.5		28	11	4	329	140	4.6		42	24	8
Cu	575	15	0.9		5	4	5	659	29	1.9		5	7	11
Co	101	29	0.29		29	18	15	44	48	0.21		48	35	27
Ni#			63.3	58.1	72	58	26			70.5	63.3	80	63	80
Co#			10.8	26.3	21	26	26			3.1	10.8	11	11	11
Ol Ni ppm		530		135	279	105	38		1392		532	421	241	336
Opx Ni ppm		97		9	51	19	7		329		10	99	57	79
Ol Mg#		79.8		72.2	79.8	77.2	72.2		81.0^		79.8	77.0	77.9	79.8
SCS			0.8*			2.6	1.0					ĺ	2.1	6.0
SS					0.3	0.2	0.2					0.7	0.2	0.3
R factor					319							145		
F%					99.7	90.6	79.8					99.3	89.4	95.1

Table 30. Porrasniemi models.

Obs. = observed; Ol=Olivine; Opx=orthopyroxene; SCS=100*sulphide/(sulphide+olivine) in the segregated material; SS=total amount of sulphides segregated vs. initial melt =100;F%=melt remaining, initial =100. Fract. 1= fractional segregation model, the difference between observed and modelled in Ni# and Co# is minimized; Fract. 2 = fractional segregation model, the difference between observed and modelled in Co# and Mg# of olivine is minimized. *Average sulphide content of barren cumulates. O Other values for initial from Laukunkangas except Mg# of olivine, which in Laukunkangas is 77.0.



Figure 137. <u>a)</u> 100*sulphide/(sulphide+olivine), SCS, of the segregated material in the fractional segregation model Fract. 1 vs. average normative sulphide content of barren cumulates. <u>b)</u> Total amount of segregated sulphides according to fractional segregation model Fract. 1 vs. average normative sulphide content of barren cumulates.

PART III: PRACTICE

12 FERTILITY ANALYSIS

The case studies support the generally accepted models and requirements of ore formation. In each fertile case, the requirements reviewed in chapter 3 have been fulfilled: 1) magma has been primitive, 2) there has been a sulphide saturation mechanism and process, 3) sulphides have equilibrated with a large amount of magma, and 4) sulphides have segregated and accumulated. Discrimination of fertile and barren intrusions – the *fertility analysis* – is based on the requirements as shown in Figure 138.

To utilize the differences observed between fertile, subeconomic and barren intrusions in exploration in practice, discrimination parameters have been put into numerical and logical format. Instead of identifying sample-by-sample whether it derives from a barren or fertile target, key figures presenting the whole target have been calculated. The method is termed population analysis, because the analysis is done for each target, i.e. sample population, separately. This methodology was developed already in the GeoNickel project (Aarnisalo et al. 1999). Each analysis step includes preliminary screening where extremes and outliers and other nonrepresentative samples are screened out from the sample population. Commonly ore samples and non-cumulates are also screened out. This is followed by additional screening to condense the data set to include samples, which are representative in terms of the feature studied. For example, only olivine cumulates are left. Finally, the key figure is calculated using simple statistical methods. Instead of extreme and average values, non-outlier minimums and maximums and medians are used.

As the aim in this study was set to attempt computerised semi-automated screening of databases, discrimination parameters are defined unambiguously. Each of the parameters is bound to physical process related to ore formation, and to stress that, each parameter is declaimed as theorem. Parameters are put in the order of tightening requirements, and the ranking method is screening. Targets passing the step in question continue to the next step, while rejected targets get for the *overall discrimination value* (*OD*) the number of the last step they have passed.

Discrimination should be based on barren cumulates. Therefore, each of the screening parameters starts with filtering out the high-grade samples (Ni>0.5 wt.% or Cu>0.5 wt.%), and non-cumulates. The latter is done by taking into analysis only samples with $MgO_n > 10$ %. This should also screen out magnetite and ilmenite cumulates, which would make the analysis more complicated and could bias especially the Co# and Ni#. If Co# and Ni# are used in calculating the value of a parameter, then only samples with cumulus sulphides are included in the analysis.

A large number of different variables were tested as the screening parameters were developed. The final result is presented here, and only some evident, rejected candidates are discussed (Table 31). In selecting the final tools, screening conditions were aimed to be as simple as possible: they do not include complicated mathematical formats (like the contamination indicators tested above), they are based solely on whole-rock chemical analyses, and on elements, which are easy to analyse, and are commonly included in whole-rock analyses. The elements used and required are: S, Ni, Co, Cu and the main rock-forming elements: Si, Mg, Fe, Al, Na, K, Ca, Fe and possibly Ti (if ilmeno-magnetite is present as cumulus mineral) and P (if apatite is voluminous).

Additionally, the discrimination parameters were designed to be used in the reconnaissance step of the exploration. Parameters do not require extensive sampling, but should work with a limited (around 20) amount of samples. Furthermore, it is considered that in this stage, samples may derive only from stratigraphic locations far away from the primitive parts and the mineralisation itself.

Uncertainties in analyses and representativeness problems in sampling were overcome by screening out the outliers of the populations. Therefore, non-outlier minimums and maximums are used and instead of average values, medians are preferred. Threshold values are tuned by limiting the number of samples in the analysis (chapter 13.1).



Figure 138. The relationship between requirements of the nickel sulphide ore formation and discrimination parameters used to distinguish fertile intrusion from the barren ones.

12.1 Parameter 1: Primitive character of the magma

The first parameter is the primitive nature of the parental magma, and it is based on theorem "Ni sulphide ore can only form from mantle derived primitive magmas (Table 31). Usually primitiveness is measured by the maximum forsterite content of olivine, maximum MgO_n content and the presence of olivine cumulates (chapter 3.1). These parameters would work in ultramafic intrusions, but in differentiated maficultramafic intrusions, which are largely composed of gabbroic, olivine-deficient cumulates, the primitiveness and the presence of olivine cumulates should also be identified in those cases, where only gabbroic parts have been sampled.

There were too few case study intrusions to test different options for the first parameter; therefore the data set of Outokumpu Mining including a total of 7517 samples from 259 Svecofennian ultramafic and mafic intrusions was used (chapter 14.3). To find out the best method to identify the presence of olivine-bearing cumulates based on gabbroic samples, the analysis was conducted on a sample set where olivine-bearing cumulates and ore samples were excluded (samples excluded where Ni or Cu content were above 0.5 wt.%, the normative olivine content above 20 % and MgO n content above 25 % or below 10 %). The best correlation with the actual maximum normative olivine content of the intrusion samples exists with the maximum mafic index of the gabbroic samples. differentiation and crystallisation Modified indices, as well the Mg# of mafic silicate, would lead to an almost equal result. Against expectation, the average ratio of normative orthopyroxene to normative pyroxenes (Opx/(Opx+Cpx)) shows a negative correlation with a maximum normative olivine content.

The primitive nature of the parental magma is measured by non-outlier maximum mafic index (Equation 14). A conservative value, 60 %, was selected for the threshold (Table 31). If the value is above 60 %, then the target passes the first criterion. If the value is below 60 %, then the target is rejected, but geophysical and other available data should be used to evaluate if sampling covers the most potential areas. If there are doubts, then sampling should be directed in areas of higher mafic index. All the case study targets pass the first test of primitiveness. Laukunkangas receives the lowest value, 76.0, which is still clearly above the threshold value.

12.2 Parameter 2: Extent of sulphide saturation

12.2.1 Contamination as an indicator

The case studies suggest strongly that crustal contamination and the incorporation of crustal sulphur is the mechanism to reach sulphide saturation. All the ore-hosting intrusions and Ekojoki and Rörmyrberget of the subeconomic intrusions indicate the presence of black schist component within and adjacent to the ore. Laukunkangas Bruvann and show direct evidence: graphite, graphite gneiss inclusions, hybrid rocks and anomalous content of V_2O_3 n, Zn, MnO n and Mo. Stormi and Ekojoki indicate black schist indirectly by a high Zn content of chromite and Rörmyrberget by an anomalously high V_2O_3 n, MnO n and Mo content in mineralised samples. Observations imply that contamination indicators would be useful in screening a fertile, contaminated intrusion.

A test was done to find out whether the Zn, Mo, MnO_n and $V_2O_3_n$ could indicate the presence of black schist component. Delta values were calculated according to the trendlines shown in Figure 34 (equations given in Table 18, p. 75; delta value = observed – calculated from the equation). Figure 139 shows the variation of delta values in each case study target and Table 32 gives the percentage of barren samples showing anomalous Zn, Mo, MnO_n and $V_2O_3_n$. However, the results are contradictory. The anomalous zinc content is the most promising one of the tested, since the percentage of Znanomalous samples correlates with the nickel content of the ore with two exceptions. At fertile Bruvann, only 2.1 % of barren cumulate samples display an anomalous zinc content and in barren Porrasniemi, about half of the samples show high Zn (Table 32).

A variation in the zinc content of chromite is illustrated in Figure 140. Though the results look promising, the method is weakened significantly by the fact that most of the analyses are from ore samples, chromite occurs only in limited parts of the intrusions and variation within sample and the grains are high.

The Bruvann and Ekojoki case studies showed that contamination evidence may be quite contradictory and are limited to only certain At Bruvann, different potential locations. contamination indicators give different results in the very same samples. For example, in a sample where sulphur isotopes, anomalous contents of black schist components (graphite, molybdenum and vanadium) indicate contamination, Sm-Nd show primitive isotopes and REE and uncontaminated mantle values. At the Ekojoki intrusion, the mineralised zone, which is located in the central part of the intrusion, indicates clear crustal contamination while the rimming part is uncontaminated. These examples show that if contamination features are used as the guide in nickel exploration, different closely located samples could lead to a totally different conclusion

Table 31. Summary of the screening parameters to distinguish a fertile intrusion from barren ones. Subscript refers to the measured variable and superscript to the subpopulation. For each analysis only barren cumulates are taken.

Parameter	1: Primitiveness
Theorem:	Ni sulphide ore can only form from mantle derived primitive magmas.
Measurement:	Parameter 1 - Marn (Equation 14)
	$1 \text{ under } 1 - \text{ maxn}_{Mafic index}$ (Equation 14)
	Theoretical range from the worst to the best: $0 \rightarrow 100$. Maxn = non-outlier maximum.
Screening:	≥ 60 %: target passes the test and is regarded as primitive or it has a possibility to include
	primitive parts.
	$\leq 60\%$: target is rejected due to its low primitiveness. Geophysical and other available data should be used to evaluate if sampling covers the most notential areas
Parameter	2: Extent of subhide seturation
Theorem:	Ni sulphide ore can only form in magmatic systems, where sulphide saturation is extensive
Measurement	v Sulphide ore can only form in magnatic systems, where surphide saturation is extensive.
measurement.	$N_{Samples} (E_{100} + 15)$
	$Parameter 2 = 100 \cdot \frac{M^{All}}{M^{All}} (Equation 15)$
	1 V Samples
	$0 \rightarrow 100$. N=number of samples.
Screening:	\geq 50 %: passes. Sulphide saturation is extensive.
	$\leq 50\%$: rejected. Target is regarded as partially or poorly sulphide-saturated, and is rejected in
D (nickel exploration. The target should, however, be evaluated for its PGE potential.
Theorem:	<u>3: NI-FICH, chalcophile undepleted magma</u>
<u>Measurement</u>	Ni supinde ore can only form from Ni-fren enalcophine-undepieted maginas.
<u>ivicasurement</u> .	$Parameter 3 = Minn_{Co\#} (Equation 16)$
	$100 \rightarrow 0$. Minn=non-outlier minimum.
Screening:	≤ 10 : passes. Magma has been nickel-rich and the target is ranked as chalcophile-undepleted.
	≥ 10 : target is chalcophile-depleted:
	- <u>if intrusion is ultramatic</u> : target is rejected
	- if intrusion is matic and differentiated and ultramatic samples are also chalcophile-depleted:
	larger is rejected.
	- II intrusion is mane and unrefermated and it samples include only mane plaglociase-
Parameter	4: Equilibration of sulphides with magma
Theorem:	Only a magmatic process can produce Ni sulphide ore and sulphide must have equilibrated with a
	large amount of magma. Towards mineralisation sulphides should become more primitive and
	less depleted.
Measurement:	Parameter $4 - Md^{Sulphide-poor} - Md^{Sulphide-rich}$ (Equation 17)
	$I \text{ that } C_{O\#} \qquad \text{ (Equation 17)}$
	$-100 \rightarrow 100$. Md = median. Sulphide-poor cumulates are those with a sulphide content lower than
	the median sulphur content of all cumulates. Sulphide-rich cumulates are those richer in sulphur
Saraaning	than the median sample.
<u>Screening</u> .	20: passes. The Co# decreases as the normative sulphide content increases, indicating that
	supmus nave equinibilities with a large amount of magma.
	(epigenetic) in origin.

Table 31 (continues) Summary of the screening parameters to distinguish a fertile intrusion from barren ones. Subscript refers to the measured variable and superscript to the subpopulation. For each analysis only barren cumulates are taken.

Parameter	5: Coeval primitiveness
Theorem:	Ni sulphide ore can form if the most primitive magma in terms of MgO is chalcophile- undepleted. Good quality ore can form in the intrusion only if the very first magma pulse entering the intrusion is the most primitive, and non-depleted with respect to base metals and sulphide- saturated.
Measurement:	$Parameter 5 = Md_{Co^{\#}}^{MgO-poor} - Md_{Co^{\#}}^{MgO-rich} $ (Equation 18)
Screening:	$-100 \rightarrow 100$. Md = median. MgO-poor cumulates are those with lower MgO than the median sample and MgO-rich -cumulates are those richer in MgO than the median sample. ≥ -1 : passes. Co# increases as MgO_n decreases, and the most primitive magma has been chalcophile undepleted. ≤ -1 : rejected. The most primitive magma has not been the most undepleted with respect to
	chalcophile elements.
Parameter	<u>6: Accumulation of sulphides</u>
Theorem:	Ni sulphide ore can only form if segregated sulphides accumulate to form a concentrated mass.
Measurement:	Parameter 6 = $Md_{N}^{MgO-rich}$ $- Md_{N}^{MgO-poor}$ (Equation 19)
Screening:	 Md = median. (100 → -100). MgO-poor cumulates are those with lower MgO than the median cumulate. MgO-rich -cumulates are those richer in MgO than the median sample. ≥0: passes. The target is classified as "accumulated sulphides", and it has the possibility to include massive-semimassive mineralisation in the contact zone. <0: rejected. The normative sulphide content increases as magnesium decreases, and the target is classified as "poorly accumulated sulphides".
Parameter	7: Fractionation or mobilisation of sulphides
Theorem:	Accumulated sulphides may fractionate and be mobilised, causing a zoned structure in the ore and its vicinity. Such features can be recorded only in intrusions containing massive-semimassive sulphide accumulations.
Measurement:	$Parameter 7 = Maxn_{Ni^{\#}}^{Co^{\#<6}} - Minn_{Ni^{\#}}^{Co^{\#<6}} $ (Equation 20)
Screening:	$0 \rightarrow 100$. Maxn = non-outlier maximum, Minn = non-outlier minimum. ≥ 35 : Intrusion is ranked as "fertile intrusion" and geophysical exploration tools should be applied instantly. ≤ 35 : rejected. The intrusion is "potential" and more sampling is required.
	<u>255</u> , rejected. The intrusion is potential and more sampling is required.

Table 32. The results of the contamination indication runs. Case refers to fertile (F), subeconomic (S) and barren (B) intrusions.

Target	Case	Code	Ni tons in	9	6 of sa	mples show	naly of	Average normative	
			mineralisation	Zn	Мо	MnO n	$V_2O_3 n$	Normative sulphides	cumulates, %
Alter_do_Chao	В	ADC	-	11.2	0.0	36.0	21.3	6.1	0.1
Bruvann	F	BRU	36720	6.7	2.6	5.6	10.6	87.2	1.6
Ekojoki	S	EJ	5520	24.0	0.0	56.0	5.3	81.8	1.4
Laukunkangas	F	LAU	52260	99.6	2.2	49.0	0.0	89.4	2.6
Porrasniemi	В	POR	-	48.2	-	14.3	6.3	82.3	0.9
Posionlahti	В	PSL	-	12.9	0.0	77.6	82.6	97.6	1.5
Rausenkulma	S	RAU	272	18.5	3.1	34.8	6.5	82.6	1.8
Rörmyrberget	S	RÖR	24000	52.3	0.0	4.5	7.4	85.2	1.4
Stormi	F	STO	51680	44.9	0.0	69.4	11.1	81.7	1.8



Figure 139. Box and whisker diagrams of potential indications of contamination of studied intrusions (codes given in Table 32, letters F, S and B below the intrusion refer to fertile, subeconomic and barren, respectively). Delta values indicate the difference between observed and predicted according to equations given in Table 27. Positive delta value is regarded anomalous and thus indicating contamination. Only barren cumulates (Ni<0.5 wt.% and Cu<0.5 wt.%) included. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20. Number in parenthesis gives the number of samples included in the diagram.

Because the results are contradictory, have large spatial variation, analyses are expensive (isotopes), and confined in the proximity of the ore, observations of the contamination features are regarded as an unreliable indication for nickel sulphide exploration and are not used as discrimination parameters.

12.2.2 Sulphides as an indicator

The main objective of the tracing contamination indicators is to find out whether the magmatic system in question has been contaminated with crustal material and thereafter become sulphur-saturated. Therefore, it is suggested that the conclusion should be made by monitoring the normative sulphide content of the barren cumulates, directly. The second theorem is: "Ni sulphide ore can only form in magmatic systems, where sulphide saturation is extensive", and this is measured by analysing the percentage of cumulates crystallised from sulphur-saturated magmas, i.e., containing cumulus sulphides (Equation 15, Table 31, p.176). To pass the second parameter, more than 50 % of samples should contain at least 0.3 % sulphides. Otherwise, the target is rejected due to its lowscale sulphide saturation. Of the case study intrusions. Alter do Chão does not pass this criterion since only 6 % of cumulates indicate crystallisation from sulphide-saturated melt. Therefore Alter do Chão gets overall discrimination, with the OD value 1 expressing that the target is primitive enough, but sulphide saturation has been only local and minor (Table 32).



Figure 140. Box and whisker diagram of zinc content of chromite in the case study intrusions. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20. Number in parenthesis gives the number of samples included in the diagram.

12.3 Parameter 3: Ni-rich, chalcophile-undepleted magma

The parental magma of the intrusion passing the first and the second screening step is mantlederived and sulphur-saturated, but it might have experienced extensive sulphide accumulation caused upstream. which has an overall chalcophile depletion. Intrusions crystallised from chalcophile-depleted magmas cannot host economic Ni-Cu mineralisation, because the Ni and *Cu tenor* would be low. The third parameter basing on statement "Ni sulphide ore can only form from Ni-rich chalcophile- undepleted magmas" screens out chalcophile-depleted intrusions (Equation 16, p. 176, Table 31). This is the second test of primitiveness (cf. parameter 1). The reason for placing the chalcophile undepletion test as the third parameter rather than second is due to its way of measurement. Chalcophile undepletion could be measured by the nickel content of mafic silicates, but the Co# is selected because the aim is that all the parameters are based on whole-rock analyses and Co# is easier to use since its absolute value is very little dependent on the fractionation of olivine in contrast to nickel content of mafic silicates (chapter 3.5, Figure 11b). In this step it is important that only the samples with more than 0.3 % sulphides are included, which requires that a large number of samples have been formed from the sulphur-saturated magma, as screened in parameter two.

Of the case study intrusions, Posionlahti and Porrasniemi are overall chalcophile-depleted intrusions, and therefore the threshold value for the non-outlier minimum value for Co# should be between 5 and 10. To be on the safe side a value of 10 is selected, thus if the non-outlier minimum of Co# is above 10, the target is identified as chalcophile-depleted.
Ultramafic intrusions have quite a narrow range of Co# and their identification is not very dependent on where samples have been collected from (Figure 141). In fertile Stormi, the units above the ore have a higher Co#, but in 75 % of samples it is below 10 (Figure 142). In the mafic intrusions the range is wide, especially in fertile intrusions like Bruvann and Laukunkangas (Figure 142). In both intrusions the parts stratigraphically above the ore are largely chalcophile-depleted, but in Bruvann the units below the ore also contain a large number of samples, which are depleted and high in Co#. If sampling is confined to these units, the screening based on Co# would lead to rejection of these targets. In Bruvann and Laukunkangas, chalcophile-depleted units are gabbroic in composition, and therefore if the analysis is based only on plagioclase-pyroxene cumulates, more primitive parts should be explored and sampled and target should be re-evaluated.

Regarding, the third step screens, Posionlahti is out and its *OD* value is 2, which refers to the parental magma being primitive and sulphursaturated but chalcophile-depleted. Porrasniemi avoids screening marginally due to some samples where the Co# is between 5 and 10.

12.4 Parameter 4: Sulphides are magmatic and equilibrated with a large amount of magma

Parameters 1-3 test the evident factors: primitiveness, sulphide-saturation and chalcophile undepletion. The fourth parameter follows the third requirement and aims to identify whether the sulphide melt has equilibrated with a large amount of silicate magma. If the sulphide liquid formation has been local and it has been able to extract metals only from a small amount of magma, then it is to be expected that the metal content in sulphides is inversely related to the normative sulphide content of the cumulates. Another explanation for such a feature could be that sulphides are epigenetic and non-magmatic in origin.



Figure 141. Box and whisker diagrams of Co# by case study targets. **a)** Co# based on bromine-methanol dissolution + AAS analyses, **b)** Co# based on XRF analyses. Only samples with cumulus sulphides are included. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20. Number in parenthesis gives the number of samples included in the diagram.



The theorem of the parameter 4 is: "Only magmatic process can produce Ni sulphide ore and sulphide melt must have equilibrated with a large amount of magma. Sulphides should become more primitive towards the mineralisation" (Table 31, p. 176). Figure 143 and Figure 144 show the relationship between the normative sulphide content and Co#. All the fertile cases show a negative relationship while barren Porrasniemi subeconomic and Rörmvrberget display or positive а poor relationship between the Co# and normative sulphide content.



Figure 142. Box and whisker diagram of Co# by zones at fertile case study targets **a**) Bruvann, **b**) Laukunkangas and **c**) Stormi. Only samples with cumulus sulphides are included. In the ultramafic intrusions like Stormi the variation in Co# is narrow and risk in incorrect identification of chalcophile depletion is minor. In mafic intrusion the units above the ore are largely chalcophile-depleted but in Bruvann also the units below the ore are (LNoZ) depleted and have high Co#. This makes the screening of targets based on non-outlier minimum Co# risky. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20. Number in parenthesis gives the number of samples included in the diagram

Parameter 4 is measured by subtracting the median Co# of sulphide-poor cumulates from the median Co# of sulphide-rich cumulates (Equation 17). The division between sulphide-rich and sulphide-poor cumulates is done according to the median sulphur content. If the value of the parameter four is negative, the target is rejected while positive value (Co# decreases towards cumulates richer in sulphides) implies that sulphides are magmatic, are equilibrated with a large amount of magma and these sulphides are more primitive towards sulphide enrichment. Again, to be on the save side, the threshold is set to -1 instead of zero.

Rörmyrberget and Porrasniemi are rejected in this stage and therefore they gain an *OD* value of 3, indicating that the parental magma has been primitive, sulphide-saturated and undepleted with respect to chalcophile elements, but sulphides have not equilibrated with a large amount of magma or equilibration has been defective. All the fertile intrusions (Bruvann, Laukunkangas and Stormi) and two subeconomic targets (Ekojoki and Rausenkulma) pass this screening step.

12.5 Parameter 5: Coeval primitiveness

Case studies show that in fertile intrusions, the most primitive magma liable for most primitive cumulates has also been the most primitive with respect to chalcophile elements. In other cases sulphide segregation has been taken place upstream, and this normally leads to small mineralisations within the intrusion, which commonly are located inside the intrusion rather than in the contact areas and are rarely economic.



Figure 143. Normative sulphide content versus Co#. <u>a)</u> Bruvann, <u>b)</u> Ekojoki, <u>c)</u> Laukunkangas, <u>d)</u> Porrasniemi. Only samples with cumulus sulphides are shown.



Figure 144. Normative sulphide content versus Co#. <u>a)</u> Posionlahti, <u>b)</u> Rausenkulma, <u>c)</u> Rörmyrberget and <u>d)</u> Stormi. Only samples with cumulus sulphides are shown.

The theorem of the fifth parameter is: "Ni sulphide ore can form if the most primitive magma in terms of MgO is chalcophileundepleted. High-grade ore can form in the intrusion only if the very first magma pulse entering the intrusion is the most primitive, nondepleted with respect to base metals and sulphidesaturated" (Table 31, p. 177). It is measured by subtracting the median Co# of MgO_n -poor cumulates using the median Co# of MgO_n -rich cumulates (Equation 18). The division between MgO n-rich and -poor cumulates is made according to the median of MgO_n . A positive value indicates that as the MgO_n content of cumulates decreases and they become more evolved, the Co# value of sulphides in equilibrium increases, implying that sulphides also become more evolved and primitiveness is coeval (Figure 145). The lower the value the higher the chalcophile depletion, which indicates a fractionation of sulphides. A negative value implies that primitiveness is not coeval and therefore, the target is rejected. The threshold is set to -1 to be on the safe side.



Figure 145. Co# versus MgO_n% to identify targets where primitiveness of silicate liquid and sulphide liquid is coeval. <u>a)</u> Bruvann, <u>b)</u> Ekojoki, <u>c)</u> Laukunkangas, <u>d)</u> Rausenkulma, <u>e)</u> Stormi and <u>f)</u> Posionlahti.

Values less than -1 are measured in Posionlahti and Rausenkulma, and Rausenkulma gets an *OD* value of 4, indicating that the target has been primitive, sulphide-saturated and sulphides have equilibrated with magma, but the primitiveness of sulphides and silicate magma is not coeval, which decreases the possibilities of a significant accumulation process.

12.6 Parameter 6: Sulphide accumulation

The theorem of the sixth parameter is: "Ni sulphide ore can only form if segregated sulphides accumulate to form a concentrated mass" (Table 31, p. 177). Since sulphide droplets are significantly denser than the magma and silicate minerals. the fractionation and accumulation process is driven by gravitation. The segregation and accumulation of sulphides should deplete the residual silicate magma in chalcophile elements, and therefore the variation in Co# should be wider in fertile intrusions. In Bruvann and Laukunkangas, the range of Co# is wider than in the ultramafic intrusions and in barren Porrasniemi, but in the ultramafic intrusions the range of Co# does not indicate the magnitude of sulphide accumulation, as can be seen in Figure 141. The magnitude and range of depletion as a measure of sulphide accumulation is rejected for the above reason and also because the range of Co# is highly dependent on the extent of sampling and from which part of the differentiation series the samples derive from.

In basic-ultrabasic magmatic systems the decreasing order of the specific gravity of the most common phases is sulphide >> chromite > olivine > pyroxenes > liquid = plagioclase. Chromite is an accessory phase in studied intrusions if present, but olivine is the main early cumulus mineral in all basic-ultrabasic magmatic systems. Therefore, the olivine is a suitable phase compare with sulphides. Gravitative to concentration causes olivine to be accumulated in some favourable locations like depression structures and embayments in the footwall and especially close to the magma feeder. If sulphides are enriched in the same locations, then it can be concluded that there has been favourable conditions for sulphide accumulation. In practice, the analysis is made by subtracting the normative sulphide content of MgO-richer cumulates from the normative sulphide content of MgO-poorer cumulates (Equation 19, p. 177). The division between MgO n-rich and -poor groups is done according the median MgO n. If the value of the parameter six is negative, then normative sulphide content decreases as the MgO *n* content increases, and target is classified as "poorly accumulated sulphides" and rejected. In other case, the target is classified as "accumulated sulphides", and the target has the possibility to include massive-semimassive mineralisation within the olivine cumulates and in the contact zone.

In Stormi and Laukunkangas, the normative sulphide content of the early MgO_n -rich cumulates is significantly higher than the within the MgO_n -poor cumulates (Figure 146), which refers to the accumulation of sulphides. In Bruvann and Ekojoki, the normative sulphide content is quite constant in the whole MgO_n range or rather higher within MgO_n -poor cumulates (Figure 146). The conclusion that sulphide accumulation has been poor in Ekojoki and Bruvann is in concordance with findings in the case studies. The sixth step screens out the subeconomic Ekojoki and fertile Bruvann leaving the fertile Laukunkangas and Stormi remaining. The OD value of Ekojoki and Bruvann is 5.



Figure 146. Normative sulphide content versus MgO_n% of <u>a</u>) Bruvann, <u>b</u>) Ekojoki, <u>c</u>) Laukunkangas and <u>d</u>) Stormi. Normative sulphide content is generally higher in MgO_n-rich olivine cumulates in Laukunkangas and Stormi, indicating sulphide accumulation while in Ekojoki and Bruvann the lack of such a feature refers to poor accumulation of sulphides. Notice that each figure has a unique x-axis scale.

12.7 Parameter 7: Fractionation or mobilisation of sulphides

The theorem of the seventh parameter called fractionation or mobilisation of sulphides is: "Accumulated sulphides may fractionate and be mobilised, causing zoning in the metal content and ratios of sulphides in the ore and its vicinity. Such features can be recorded only in intrusions containing massive-semimassive sulphide accumulations" (Table 31, p. 177). The fertile

intrusions of Stormi and Laukunkangas show a wide variation of Ni# in low Co# values, which is due to the mobilisation of a Cu-rich sulphide fraction or fractionation of *Mss* from the sulphide liquid. This feature is strongest within the ore, but it can also be recorded in samples some tens of meters away from the ore. The lack of this feature does not rule out the possibility of the existence

of ore within the intrusion, but its presence implies that the ore is located within the intrusion and some samples have originated from the immediate vicinity of the ore.

Parameter seven is measured by calculating the range of non-outlier Ni# within the barren cumulates with low Co# (<6, Equation 17). A wide variation of Ni# in low Co# values informs that the intrusion hosts massive-semimassive sulphide accumulation, and it is located close to the sampled parts. If the value is greater than 35, then the intrusion is ranked as a "fertile intrusion" and geophysical exploration tools should be applied instantly. Otherwise, the intrusion is "potential" and more samples are required in sites showing the highest potential (chapter 13).

The value of parameter seven is greater than 35 in Stormi (Figure 147), indicating that the sulphides have fractionated or mobilised, which requires the presence of a massive or semimassive ore. The ore is located close to the samples lowest in Co# (chapter 13). Laukunkangas gets an *OD* value of 6 and Stormi 7.



Figure 147. Box and whisker diagram of Ni# by target. Samples shown contain cumulus sulphides, Ni<0.5 wt.% and Co#<6. The number in parentheses shows the number of samples included in the diagram. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20.

12.8 Auxiliary parameters

In addition to screening parameters, four auxiliary parameters were established. While screening parameters either reject or accept the target, auxiliary parameters classify them in different cases to be further evaluated by screening parameters. In the following, these auxiliary parameters have been calculated from chemical analyses. Classification could also be based on knowledge from maps, target descriptions, ocular observations or microscopical studies. Letters A-D refer to auxiliary parameters (Table 33).

In a komatiitic environment, Ni exploration techniques differ from the ones used in intrusions. Parameter A evaluates the composition of the parental magma (Table 33). In komatiites, the Ni/Cr ratio as well as other specific geochemical tools could be used (Barnes and Brand 1999). The discrimination parameters of this study were established on the basis intrusions crystallised from basaltic and high-Mg basaltic magmas, therefore in komatiites the result of the fertility analysis should be questioned.

It is important to know whether the target is mafic or ultramafic (parameter B, Table 33). Mafic intrusions are differentiated and the most interesting ultramafic parts may be very small and hidden. To have a reliable OD, sampling should be extended in the ultramafic parts, too. Mafic intrusions also have the potential of hosting PGE deposits. Ultramafic targets are less differentiated, and sulphides do not also show such a great variety in Co#, and therefore their ranking according to discrimination parameters can be regarded more reliable. It should be remembered, however, that ultramafic intrusions have formed from magma passing through the intrusion chamber, and from this it follows that in general two samples next to each other may have crystallised from totally different types of magmas, e.g. other from sulphide-saturated and other from sulphur undersaturated.

Ore-hosting mafic intrusions may be chalcophile-depleted in their gabbroic and pyroxenitic parts, but olivine cumulates are nondepleted. Therefore it is important to know, whether there are olivine cumulates within the dataset. Parameter C answers for that (Table 33). If the dataset includes normative olivine ad-, meso- or orthocumulates, then the mafic and chalcophile element -depleted target is rejected. Otherwise, more sampling is needed from the most primitive cumulates.

Table 33. Auxiliary parameters used in classifying intrusions.

Parameter	A: Parental magma
Measurement:	Parameter $A = Maxn_{Forsterite of normative olivine}$ (Equation 21)
Classification: Discussion:	Maxn = Non-outlier maximum >92 = Komatiitic (K), 88-92 = Picritic (P), 78-88 = Basaltic (B), <78 = Andesitic (A) Fertility analysis was developed for intrusions crystallised from basaltic and high- Mg ("picritic") melts. If the parental magma is komatiitic, analysis should be questioned.
Parameter	B: Intrusion type, mafic/ultramafic
Measurement:	Parameter $B = Md_{Normative plagioclase}^{Cumulates}$ (Equation 22)
Classification: Discussion:	$Md=Median. \le 10$ ultramafic (UM), >10 mafic (M) Ultramafic intrusions show a narrow range in Co#, and a conclusion on the chalcophile depletion can be made on the basis of a small amount of samples. In mafic intrusions, Co# may vary significantly within the intrusion, and the conclusion should be made after due consideration.
Parameter	C: The most primitive cumulate
Measurement:	Parameter $C = Maxn_{Normative olivine}^{Cumulates}$ (Equation 23)
Classification:	Maxn=Non-outlier maximum >93% adcumulate (A); 75-93% mesocumulate (M); 50-75% orthocumulate (O); 25-50% olivine-bearing cumulate (B); 10-25% cumulus olivine ((o)); <10 no olivine cumulates (-).
Discussion:	If the target is chalcophile-depleted and the intrusion type is mafic, then one needs to evaluate if primitive cumulates are included in the sample set. If value is A, M or O chalcophile-depleted the target is rejected. Otherwise more sampling is needed from the most primitive cumulates.
Parameter	<u>D: Dominant pyroxene, Opx/Cpx</u>
Measurement:	Parameter $D = Md_{100*Opx/(Opx+Cpx)}^{Cumulates}$ (Equation 24)
Classification: Discussion:	Md=median If value is greater than 50, then target is orthopyroxene (Opx) dominating (normative), otherwise clinopyroxene (Cpx) dominating (normative). Mafic intrusions dominated by (normative) orthopyroxene seem to be, for unknown reason, more favourable for Ni-sulphide ores than the ones where (normative) clinopyroxene is the main pyroxene

					C) The mos	st olivine-rich			
Target	A) Parental_N	lagma	B) Intrus	 B) Intrusion type 		(normative)	D) Domina	D) Dominant pyroxene	
Alter_do_Chao	PICRITIC	89.3	М	23.0	Ad	98.0	Срх	12.6	
Bruvann	PICRITIC	87.9	М	22.0	Meso	90.7	Opx	90.4	
Ekojoki	BASALTIC	81.9	UM	6.8	Meso	84.5	Срх	48.0	
Laukunkangas	BASALTIC	77.0	М	38.0	(0)	12.3	Opx	90.1	
Porrasniemi	BASALTIC	79.8	М	15.1	(0)	24.6	Opx	55.2	
Posionlahti	BASALTIC	80.7	UM	3.3	Ad	96.2	Opx	86.3	
Rausenkulma	BASALTIC	78.9	UM	7.5	Ortho	72.2	Срх	32.5	
Rörmyrberget	PICRITIC	89.6	UM	8.3	Ortho	55.5	Opx	95.1	
Stormi	BASALTIC	83.9	UM	6.3	Meso	81.3	Opx	64.8	

Table 34. The values of the auxiliary parameters of the case study targets.

Parameter C, the nature of the most olivinerich cumulate, also implies that about magma dynamics. Olivine adcumulates, containing more than 93% olivine, have formed in vigorously flowing magma systems, where the intercumulus liquid has been constantly removed, while in orthocumulates the cumulus minerals have trapped the intercumulus liquid. Generally the former means more magma, lower viscocity, higher temperature, which all favour the formation of Ni-sulphide ore.

Mafic intrusions dominated by noritic rocks seem to be more favourable for the occurrence of Ni sulphide deposit than gabbroic rocks. This is monitored by parameter D, the ratio of normative orthopyroxene to the sum of normative ortho- and clinopyroxene. This ratio was not set as discrimination parameter, because the test data was too small, and the general theory why a orthopyroxene- dominated intrusion would be more prospective, is not well established, though it has been proposed earlier by Mäkinen (1987). In evaluating the PGE potential of mafic the orthopyroxene-dominating intrusions intrusions would be more prospective, because they indicate a boninitic, boninite-like or "Ttype" parental magma (Sharpe and Hulbert 1985, Alapieti 2005, Naldrett 2005).

12.9 Ranking of the case study targets according to their ore hosting potential

The value of each discrimination parameter and overall discrimination value gained, OD, of the case study targets are summarised in Table 35 and in Figure 148. Ore samples (Ni>0.5% or Cu>0.5%) have been excluded from the discrimination therefore the targets are comparable. In order to set the targets, which were omitted in the same step, in order of superiority, a decimal place is added into the overall discrimination value, OD. The decimal place describes how well the target has passed the last qualified step. The OD is calculated from the last passed step values according to this equation: OD = Step + 0.499*(D-T)/(Max-T)

(Equation 25)

where the Step is the number of the last qualified step, Max is the best possible value of the discrimination parameter, D is the value of discrimination parameter and T is the threshold value. The maximum decimal place is 0.499 to make the difference between discrimination steps big enough and to prevent the change in the integer part of the *OD* as the number of decimals is adjusted.

The decision tree of discriminating fertile intrusions from barren ones is shown in Figure 149 and 150. The decision is based on discrimination parameters as discussed in chapters 12.1-12.7. Auxiliary parameters are used to evaluate whether the decision can be regarded as reliable, whether sampling is adequate and whether the PGE potential of the target would require special attention.

The order of superiority of the targets according to the discrimination parameters developed is 1) Stormi, *OD*=7.31; 2) Laukunkangas, 6.00; 3) Bruvann, 5.05; 4) Ekojoki, 5.04; 5) Rausenkulma, 4.03; 6) Rörmyrberget, 3.39; 7) Porrasniemi, 3.20; 8) Posionlahti, 2.48 and 9) Alter do Chão, 1.49. The case study targets show that an OD equal or greater than 6 indicates that the target hosts nickel ore. If the OD is 5.0-5.5, then the target is a boundary case, either minable or subeconomic. An OD of 3-4.5 indicates a possibility for poor mineralisation and the targets, whose values are less than 3, are barren (Figure 150).

Table 35. The values of the discrimination parameters and number of samples included in analysis (in parentheses). Passed steps are boxed. Parameters: [1] Primitiveness (max mafic index), [2] Sulphide saturation% (percentage of sulphide-saturated samples), [3] Undepleted magma (min Co#), [4] Magmatic sulphides (Co# vs. \$), [5] Coeval primitiveness (Co# vs. MgO_n), [6] Sulphide accumulation (\$ vs. MgO_n), [7] Sulphide fractionation (Ni# range). OD is the overall discrimination value, i.e. integer part is the number of the last passed step and decimal part (used to rank targets, which have failed in the same steps) describes how well it has passed the last step (0.00-0.500). Type: Subec.=subeconomic, Ultram.=ultramafic.

Target	Туре	OD	N Threshold >	[1] >60	[2] >50	[3] <10	[4] >-1	[5] >-1	[6] <0	[7] >35
Alter do Chão	Barren Mafic	1.49	(190)	99.5 (90)	2.2 (90)	14.6 <i>(2)</i>	- (2)	- (2)	0.05 (90)	- (0)
Bruvann	Fertile Mafic	5.03	(222)	96.1 (188)	88.3 (188)	2.7 (166)	4.6 (166)	7.9 (81)	0.03 (188)	16.4 <i>(33)</i>
Ekojoki	Subec. Ultram.	5.01	(106)	96.4 <i>(81)</i>	85.4 <i>(82)</i>	1.3 (12)	8.2 (12)	7.4 (35)	0.16 <i>(82)</i>	13.3 (29)
Laukun- kangas	Fertile Mafic	6.00	(789)	76.0 (247)	91.5 <i>(364)</i>	0.0 (30)	13.9 <i>(30)</i>	12.4 (166)	-0.29 (364)	26.6 (145)
Porras- niemi	Barren Mafic	3.20	(64)	89.6 (60)	77.0 (61)	6.1 (16)	-3.8 (16)	3.1 <i>(22)</i>	0.05 <i>(61)</i>	- (0)
Posion- lahti	Barren Ultram.	2.50	(247)	99.0 (118)	99.6 (241)	15.5 <i>(24)</i>	5.4 (24)	-4.6 (120)	-0.09 (241)	- (0)
Rausen- kulma	Subec. Ultram.	4.02	(184)	95.8 <i>(99)</i>	69.2 (182)	2.6 (82)	5.7 (82)	-1.6 (63)	0.05 (182)	34.6 <i>(24)</i>
Rörmyr- berget	Subec. Ultram.	3.39	(214)	98.4 (188)	86.2 (188)	1.5 (162)	-1.5 (162)	5.4 (36)	0.71 <i>(188)</i>	15.5 (45)
Stormi	Fertile Ultram.	7.31	(424)	97.3 (105)	95.3 (233)	1.0 (13)	6.8 (13)	5.8 (111)	-0.09 (233)	50.5 (143)



Figure 148. The values of the discrimination parameters in the case study targets. The column indicates the value of the parameter and each figure has been prepared so that the value is getting better towards right. A threshold value is given in the header in parentheses and shown as a vertical line. The dark grey column colour indicates that target has passed all the parameters so far and passes the one in question, too. The white bar colour indicates that the target has failed to pass some discrimination parameter and the OD value, overall discrimination value, i.e. the last passed parameters, is given on the right side of the bar.



Targets, which are primitive but not extensively sulphide-saturated, having an OD value 1.000-1.499, should be re-evaluated in terms of parental magma and intrusion type (Figure 150). If the parental magma is komatiitic, then exploration and evaluation methods of komatiites should be applied. If the parental magma is basaltic, the intrusion is mafic and the dominant normative pyroxene is orthopyroxene, then the intrusion may be a large layered intrusion of boninitic affinity, and its PGE potential should be evaluated.

In each case, the representativity of the sampling has to be evaluated. If there are doubts that the sample set covers the most primitive parts of the target, then resampling followed by assaying and a rerun of the fertility analysis should be considered. Discrimination step three, undepleted magma, is critical in mafic intrusions. If the maximum normative olivine content is less than 10%, then one should consider whether there is a possibility for the existence of olivine-bearing cumulates, and if so, they should be sampled and the target re-evaluated.



Figure 150. Decision tree for the implementation of the overall discrimination index in nickel exploration.

13 LOCALISING THE ORE AND ESTIMATING ITS GRADE AND SIZE

13.1 Methods for localising the Ni-Cu ore

The best methods for localising a sulphide nickel ore within the fertile intrusions identified are generally geophysical ground or down-hole surveys. The Ni sulphide ores are magnetic because of the high amount of monoclinic pyrrhotite, but their signal may be obscured by abundant magnetite in barren cumulates due to serpentinisation of olivine. Electromagnetic conductivity of massive and semimassive sulphide deposits may be masked by graphite gneisses, which are common in the surroundings.

Nickel sulphide ore is not very big in size compared to the intrusion itself. The horizontal projection of the ore is in Bruvann 0.05 km², which is less than 0.1% of the intrusion and 5% the Bruvann block. In Stormi of and Laukunkangas, the ore comprises 2-5 vol.% of the intrusion. For the above reasons. petrochemistry can be useful and is necessary to point out the most potential locations, which deserve special attention.

In Stormi and Laukunkangas, the Co# decreases towards the ore and logarithmic equation can be fitted between the stratigraphic distance and Co#::

Distance to the ore = 190*Ln (Co#)-235.

(Equation 26)

The correlation between the calculated and actual stratigraphic distance to the ore is moderate as shown in Figure 151 ($R^2=0.64$).



Figure 151. <u>a)</u> Correlation between stratigraphic distance to ore and Co#. Fitted equation y=190*Ln (Co#)-235. <u>b</u>) Actual stratigraphic distance *vs.* model distance to the ore, Laukunkangas and Stormi cases shown (legend as in a). <u>c</u>) Outcrop samples (n=28) of Laukunkangas plotted on geological map and ranged according to distance to the ore. SE corner of the intrusion comes up as the most prospective area. Width of the map is 1 km.

Geological Survey of Finland, Bulletin 402 195 From Genetic Concepts to Practice ...



Figure 152. In Bruvann the stratigraphic distance of the sample to the ore is much more complicated to predict on the basis of rock chemistry. a) Co# has no correlation to distance to the ore, curve shown is the model curve fitted based on Stormi and Laukunkangas (Figure 151a). b) The ratio of normative clinopyroxene to normative pyroxenes decreases towards the ore. Plot mark according to the most voluminous normative cumulus mineral (a=Cpx, b=Opx, o=Olivine, p=Plagioclase). Fitted straight line through origin (y=6*x). c) Distance to the ore vs. MgO_n content. Plot mark as in b. d) Calculated model distance to the ore against stratigraphic height. Solid line (avg) is running average. Ore samples are excluded in the figure. Plot mark as in b.

At Bruvann, the correlation between Co# and the distance to the ore is non-existent (Figure 152a) and it is much more complicated to find a parameter, which would point towards the ore. The correlation analysis shows that the best figures to explain the distance to the ore are CaO_n , normative clinopyroxene, sum of normative clinopyroxene and plagioclase, and the ratio of normative clinopyroxene to normative orthopyroxene, MgO n content and Co#. The normative pyroxene ratio and MgO_n give the best fit, and multivariate analysis gives the following equation for the model distance:

Model distance (m)

$$=2.2*(Co\#+100*Cpx/(Cpx+Opx)-MgO_n%)+90$$

(Equation 27)

The sample-by-sample correlation between the calculated and actual stratigraphic distance to the ore is quite poor, but seen against the stratigraphic height, the model succeeds in

indicating the highest potential in the Middle peridotite zone while the lowest potential is reported in the Gabbro zone (Figure 152d).

Figure 153 shows the variation in the the calculated model distance to ore in the case study targets. Calculation is relevant to intrusions where the overall discrimination index, OD, is equal to

or greater than 5: in Stormi, Ekojoki, Laukunkangas and Bruvann. If the OD is 7 (Stormi) exploration should be directed in areas having the lowest "model distance to ore". In targets where the OD is 5 or 6 lower OD points towards the most potential sites.





Figure 153. Box and whisker diagram of the variation in the calculated model distance to ore in metres. For explanation of the box and whisker diagram see terms and nomenclature in Chapter 20. Number in parenthesis gives the number of samples included in the diagram

13.2 Estimating the grade and tonnages

The case study intrusions are too few to seriously develop a methodology for the estimation of grade and tonnages of a deposit. However, some general trendlines are discussed. Häkli (1963) showed that the *Ni tenor* correlates with the Ni content of olivine. Also, the Co# correlates negatively with the *Ni+Cu tenor* (Figure 154a). From the fitted equation it is possible to deduce the Ni and Cu content of the sulphide fraction based on the Ni# and Co# (Equation 28 and Equation 29).

$$Ni _SF\% = Ni\#\times 0.23 \times Co\#^{-0.95} \qquad Equation \ 28$$
$$Cu _SF\% = \left(1 - \frac{Ni\#}{100}\right) \times 23 \times Co\#^{-0.95} \qquad Equation \ 29$$

Within an intrusion, the Co# correlates negatively with the Ni wt.% (Figure 154a). In Ni>0.1% Co# does not decrease significantly. Ni# correlates weakly with the Ni wt.%.

It is possible to forecast the Ni#, Co#, Ni_SF% and Cu_SF% of the ore at least roughly on the basis of samples with cumulus sulphides and Ni<0.5% (Figure 155). The estimated Co# of the ore is slightly lower than the actual Co# in the ore.

The actual Ni and Cu grades are dependent on the sulphide content of the ore in addition to tenors. As the tenors can be forecast with reasonable accuracy the actual grade could be evaluated if the sulphide content could also be





Figure 154. <u>a)</u> Correlation between Ni+Cu tenor versus Co# of the case study intrusions. The equation of the best fit curve is given in the figure.

b) Co# has negative correlation with Ni wt.%.

c) Ni# has a weak positive correlation with Ni wt.%.

forecast. A reliable method for that was not found. The Ni+Cu in the Svecofennian deposits mined has been mainly around 1% with Hälvälä an exception with Ni+Cu=1.95. The best

correlation with the nickel content of the ore in metric tons and Ni grade in wt.% can be found with the *OD* value (Figure 156).

14 TESTING THE PRACTICABILITY OF THE OD INDEX

14.1 Effect of number of samples and analysis methods

The data sets of the case study targets were used to test the dependence of the value of the overall discrimination index on the number of samples and analytical methods. The case study samples were analysed for sulphidic nickel, cobalt and copper using the bromine-methanol dissolution (Penttinen et al. 1977), which is quite exceptional, since commonly only whole-rock analyses with XRF and Leco are available. Hence the first test (1a) used only whole-rock analyses

198 Geological Survey of Finland Bulletin 402 Pertti Lamberg



Figure 155. Comparison of estimated Ni#, Co#, Cu_SF% and Ni_SF% with actual tenors in the ore.

compared to the zero case utilising all the available data. This restriction reduced the number of samples significantly in Laukunkangas (789 \rightarrow 249) and in Stormi (424 \rightarrow 105, Table 36) and accordingly the *OD* value changed in four cases of nine: it decreased one unit in Ekojoki (5 \rightarrow 4), Porrasniemi (3 \rightarrow 2) and Stormi (7 \rightarrow 6) and increased significantly two units in Rörmyrberget from 3 to 5.

In the next test (1b), the number of samples with whole-rock analyses was reduced randomly but stepwise to given a fraction of the original (Table 36). In five cases out of nine, in Alter do Chão, Laukunkangas, Porrasniemi, Posionlahti and Rörmyrberget, the *OD* value does not change compared to test 1a although the number of samples was reduced down to 6-25. In Ekojoki, Rausenkulma and Stormi the *OD* value changes when the number of samples is reduced to <50. In Ekojoki, the *OD* value first increases by 1 unit, but finally decreases by two units compared to test 1a. In Rausenkulma *OD* value increases by one and two units. The *OD* value is most sensitive to the number of samples in the targets that display *OD* values of between 4 and 6, while *OD* values of 1-2 are very resistant to the reduction of sample number.





Figure 156. Within tested parameters OD has the best correlation with ore content and Ni grade. <u>a)</u> Ore content, million tons, versus OD. <u>b)</u> Ni grade (%) of the ore versus OD. <u>c)</u> Ni content (tonnes) versus OD.

The next test (1c) included only outcrop samples. From Alter do Chão every second profile was selected and from those every second sample was taken in the test. However, the outcrop samples are scarce in Bruvann, Ekojoki and Posionlahti and Laukunkangas is practically without whole-rock chemical assays, and hence in these cases shallow depth samples were included (Laukunkangas < 25 m, Bruvann < 10 m, Ekojoki < 50 m and Posionlahti <80 m). This corresponds to a typical reconnaissance study with a light sampling rig used for shallow level hard rock. The number of samples selected in this way varied in the different targets from 6 to 33. The result is almost identical with test 1a (Table 36). In Bruvann and Stormi, the OD value is significantly lower than and would result in the targets being rejected. Ekojoki and Rörmyrberget receive a unit higher *OD* value indicating the potential for disseminated ore.

Gabbroic intrusions have a risk to be ranked out already at the first level of the fertility analysis. With this in view, the different intrusions were tested using a sample set that was reduced stepwise from the MgO_n -rich end (1d, Table 36). In the case of Laukunkangas, as the number of samples drops from 187 to 125, the value of the OD index drops from six to zero. At Bruvann the drop comes later, when the number of samples approaches 20. In ultramafic intrusions, the largest change takes place at Rausenkulma where the OD value increases from

Table 36. Values of the overall discrimination index and number of samples in different tests, which analyse the sensitivity of the fertility analysis on the number of samples. Percentage values indicate the relative amount of samples included in the test compared to the "All analyses / XRF" test. Italics indicate that the OD value differs from the "All analyses / XRF" by 1 unit and underline that difference is significant, i.e. \geq two units.

Analysis/Target	ADC	BRU	EJ	LAU	POR	PSL	RAU	RÖR	STO	
-OD-value -										
0) All samples and assays	XRF+BM	1.494	5.045	5.042	6.001	3.195	2.484	4.034	3.387	7.307
1a) Whole-rock assays	XRF	1.481	5.029	4.047	6.009	2.250	2.482	4.031	<u>5.024</u>	6.002
1b) Random sets	90%	1.481	5.028	4.045	6.008	2.259	2.490	4.037	5.021	6.001
	75%	1.481	6.000	4.045	6.009	2.211	2.488	4.021	5.019	6.008
	50%	1.480	6.001	4.042	6.010	2.200	2.482	5.016	5.027	6.009
	25%	1.479	6.001	5.069	6.008	2.166	2.499	<u>6.001</u>	5.029	<u>3.303</u>
	10%	1.467	6.001	<u>2.250</u>	6.023	2.333	2.499	<u>6.002</u>	5.027	<u>3.281</u>
1c) Outcrops		1.480	<u>2.100</u>	5.012	6.006	2.250	2.333	4.016	5.045	<u>3.281</u>
1d) <i>MgO_n</i> -poor samples	90%	1.480	6.000	4.056	6.003	2.259	2.480	4.033	5.025	5.016
	75%	1.480	6.001	4.056	6.002	2.255	2.477	<u>6.000</u>	5.027	<u>4.039</u>
	50%	1.275	6.003	5.048	<u>0.000</u>	3.007	2.499	<u>6.001</u>	5.030	6.000
	25%	1.022	6.001	<u>2.399</u>	<u>0.000</u>	3.007	2.499	<u>6.002</u>	6.004	<u>3.372</u>
	10%	1.045	<u>0.000</u>	<u>2.374</u>	0.000	3.007	2.499	<u>2.100</u>	6.009	<u>3.372</u>
1e) <i>MgO_n</i> -rich samples	90%	1.481	5.027	4.056	6.014	2.245	2.480	4.034	5.019	6.005
	75%	1.481	5.014	4.056	6.021	2.239	2.477	4.038	5.018	6.006
	50%	1.481	5.014	5.038	6.022	2.299	2.465	4.038	5.005	6.012
	25%	1.481	6.000	3.342	6.005	2.250	2.499	<u>2.115</u>	5.017	6.012
	10%	1.481	4.024	3.342	5.004	2.071	2.499	<u>1.435</u>	<u>3.283</u>	<u>3.270</u>
		- Numb	er of sai	nples -						
All samples and assays	XRF+BM	190	222	106	789	64	247	184	214	424
1a) Whole-rock assays	XRF	91	188	81	249	60	118	99	188	105
1b) Random sets	90%	82	169	73	224	54	106	89	169	95
	75%	68	141	61	187	45	89	74	141	79
	50%	46	94	41	125	30	59	50	94	53
	25%	23	47	20	62	15	30	<u>25</u>	47	<u>26</u>
	10%	9	19	<u>8</u>	25	6	12	<u>10</u>	19	<u>11</u>
1c) Outcrops		23	<u>10</u>	20	17	16	6	33	11	<u>10</u>
1d) MgO_n-poor samples	90%	82	169	73	224	54	106	89	169	95
	75%	68	141	61	187	45	89	<u>74</u>	141	<u>79</u>
	50%	46	94	41	<u>125</u>	30	59	<u>50</u>	94	53
	25%	23	47	<u>20</u>	<u>62</u>	15	30	<u>25</u>	47	<u>26</u>
	10%	9	<u>19</u>	<u>8</u>	<u>25</u>	6	12	<u>10</u>	19	<u>11</u>
Te) MgO_n-rich samples	90%	83	170	74	225	55	107	90	170	95
	75%	69	142	62	188	46	89	75	142	80
	50%	46	94	41	125	30	59	50	94	53
	5070	40	01		120					
	25%	24	48	21	63	16	30	<u>26</u>	48	27

4 to 6 as the number of samples decreases from 89 to 74. At Stormi the OD value swings restlessly between 3 and 6.

The final test (1e) demonstrates the case when sampling is concentrated in the most primitive

14.2 Specific tests on the Råna intrusion

The second set of tests were made with the data of the Råna intrusion in order to define whether the discrimination parameters work in a large intrusion to a) evaluate the overall ore hosting potential of the intrusion, b) rank the different targets within the intrusion, and c) test whether the most potential locations can be pinpointed.

Sample data from the Råna intrusion was collected during the exploration campaign of Nikkel Og Olivin from the targets of Arnes, Arneshesten, Bruvann, Lake Bruvann, Råna, Rånbogen and Tverfjell as depicted in Figure 22 (Karppanen et al. 1999). The Tverfjell samples and analyses are from the study of Barnes (1985). The sampling in all targets was concentrated on the most primitive olivine-rich cumulates and hence the sampling was restricted almost totally to the Ultramafic Series, but Bruvann, Arnes, Arneshesten and Tverfjell also include samples from the Mafic Series.

The result of the ranking is given in Table 37 and illustrated in Figure 157. The *OD* value of the target is identical whether the ore samples (Ni or Cu >0.5%) are included or not in the analysis (Table 37). Sulphide saturation is an overall feature of the Råna layered intrusion and therefore all the targets pass the second step. Arneshesten is an overall nickel-depleted area and cobalt analyses were not available in Tverfjell, hence both targets do not pass the third stage of discrimination and their *OD* value is 2. In Rånbogen, Co# is higher in MgO_n -rich samples, which indicates that primitiveness is not coeval, and the target fails to pass the fifth step obtaining an *OD* value of 4. Bruvann and Lake Bruvann do parts of the intrusions. When the size of the sample set is reduced from the MgO_n-poor end down to around 20 samples (50 in Rausenkulma), the OD values remain in all targets within one unit compared to test 1a.

not indicate sulphide accumulation and they fail to pass the sixth step, while Råna and Arnes pass this step. Three of the targets in the Råna intrusion get a higher ranking than the ore-hosting Bruvann.



Figure 157. OD values of the targets in the Råna intrusion. Råna and Arnes have the highest OD values of 6.

The results show that the features related to the ore formation process are widely visible in the Råna intrusion but the different parts give different *OD* values. Several other targets of the Råna intrusion get as high an *OD* value as the exploited Bruvann. When the *OD* tolerance ± 1 is considered, the fertility analysis succeeds to point the north and northwest sections of the Råna intrusions as the most promising parts.

In Bruvann the model distance to the ore brings out the ore-hosting olivine cumulates (Figure 152). At Arnes the fifth, sixth and seventh olivine cumulates calculated from the north contact show highest prospectivity (Figure 158). However, the drilling carried out in the target did not uncover any significant sulphide accumulation though thin intersections with high nickel and copper contents were encountered (Karppanen at al. 2000).

In the Råna intrusion, the most primitive and base metal non-depleted cumulates are located in all the targets quite far away from the primary contact, which forecasts that if sulphide enrichment is encountered, it is either of low grade, i.e. disseminated type, or small in size and thus not very interesting. This conclusion based on a quite rapid assessment of existing lithogeochemical data is in harmony with the results of twenty years of nickel sulphide exploration in the Råna intrusion.

Table 37	OD values	and model	distance to	the ore	of the t	argets in	the De	ana intr	usions	Figura	22
1 auto 57.	OD values	and mouch	uistance to	the ore	or the t	argets m	the re	ana mu	usions,	riguit	44.

	All samples		Ore samples exclu	ded	Model distance	Model distance to ore, m		
Target	OD	n	OD	n	Min	Median		
Råna	6.001	32	6.001	30	27	81		
Arnes	6.001	124	6.001	121	14	86		
Lake Bruvann	5.029	202	5.036	191	31	107		
Bruvann	5.028	204	5.030	190	18	112		
Rånbogen	4.057	14	4.049	13	36	126		
Arneshesten	2.277	9	2.277	9	42	89		
Tverfjell	2.000	135	2.000	135	7	130		



Figure 158. Geological map of the Arnes. Sample points are shown as circles. whose size indicates the model distance to the ore, meters. The bigger the circle, the smaller the model distance, values range from 14 to 332 m. The peridotitic layer (PRD) in the central part of the figure seems the most critical part since the model distance to the ore is very low in several samples.

14.3 Svecofennian intrusions of Finland

The third test is based on large lithogeochemical database of the Svecofennian orogenic mafic-ultramafic intrusions of Finland including a total of 7517 samples. Only targets with more than ten samples were included in the test and samples with Ni>0.5% or Cu>0.5% were excluded in the test material. The total number of targets analysed was 353. Table 38 summarises the results and the location of targets with different OD values is illustrated in Figure 159.

The Svecofennian mafic-ultramafic intrusions have the highest density in narrow belts: the Pori-Vammala-Kylmäkoski belt in Southwest Finland, the broken belt from Parikkala via Laukunkangas to Kotalahti in Eastern Finland and the Sulkava-Juva belt southwest of Kotalahti (the Lumpeinen Niinimäki intrusions). In Häme and and Osterbothnia (e.g. Hitura) the intrusions are more scattered and generally display lower OD values. Most of the intrusions outside the belts do not pass the first criterion and have an OD value of zero. The gabbroic to hornblenditic intrusions with lacking ultramafic parts are minor mafic cumulates of voluminous grantic to tonalitic intrusions.

The Svecofennian orogenic mafic-ultramafic intrusions of the mentioned main sulphide belts stand out clearly on the basis of three first parameters. Only about 10% of the targets do not pass the criterion of primitiveness. About 77% of the Svecofennian intrusions display an extensive sulphide saturation and pass the second criterion as well. The third parameter, undepleted magma, decreases the percentage of the passed targets to 54%. The fourth parameter, which tests whether the sulphides are equilibrated with a large amount of magma, decreases the percentage of passed targets significantly to 23%. The distribution of the targets with an OD value of four or higher define in South-eastern Finland the narrow Pori-Kylmäkoski belt extending from Ahlainen, slightly north of Pori, via Vammala to Kylmäkoski. In the Häme area, very few targets

display an *OD* value of 5 or higher. In Eastern Finland, the Juva belt and the belt from Parikkala via Laukunkangas and Kotalahti to Karttula can be recognized. Only a few tar targets with an *OD* value of 5 or higher exist in the area north and northwest of the Granitoid Complex of Central Finland. Two of them are in the Hitura area and Oravainen on the west coast.

A common feature in the discrimination parameters of exploration are that the target tends to become more favourable the more samples there are. According to the test with Svecofennian intrusions, the fertility analysis seems to avoid this problem since no correlation can be seen between OD and the number of samples (Figure 160c).

Intrusions with exploited Ni-Cu ores, display OD values of four or higher (Figure 159) and the average value is 5.88. The average OD of the intrusions with subeconomic Ni-Cu deposits is 5.01 (range is 0-6) and that of barren intrusions 2.95 (0-7). The rest of the fertile and mined intrusions besides Stormi and Laukunkangas are discussed in the following.

The OD value of Hitura (Isohanni et al. 1985) is 4.018. The value of parameter five, coeval primitiveness, is -1.78 whereas the threshold is >-1.00. The Co#-MgO n trend of Hitura is clearly positive (Figure 161a) and the Co# vs. Ni# graph (Figure 161b) shows that the sulphide to olivine ratio in Hitura has been high. These features indicate that the sulphide segregation and olivine fractionation history of Hitura has been rather complicated. The most primitive silicate liquid had experienced sulphide segregation, while the most primitive sulphides accumulated within less primitive olivine cumulates. Partly this is because the ore is within the intrusion margins, which are in general less magnesian than the barren inner parts of the intrusion (Isohanni et al. 1985). However, this is not the whole picture, since high-MgO *n* olivine cumulates are common within the ore (Figure 161a). A multistage model

Table 38. The testing results of Svecofennian intrusions. Only targets with more than 10 analysed samples were included. The group with OD zero includes targets which do not pass the first criterion, otherwise the OD number refers to the last criterion the target passes.

Target	Passing%	Stan	OD		Examples
Target		siep	Ν	%	
1. Primitivanass	00.1	0	35	9.9	Porkkala
1. I IIIIIIIVeness	90.1	1	40	13.0	Forssa, Alpua, Leineperi
2: Extent of sulphide saturation	77.0	2	82	23.2	Posionlahti, Kauhajärvi, Turunen
3: Ni-rich, chalcophile undepleted magma	53.8	3	108	30.6	Ahlainen, Parikkala, Hyvinkää
4: Sulphides are magmatic and equilibrated with large amount of magma	23.2	4	14	4.0	Hitura, Tyrisevä, Kuokkala, Honkola, Suvitie, Sääksjoki
5: Coeval primitiveness	19.2	5	28	7.9	Kotalahti, Sappee, Sahakoski, Ekojoki, Laukunlampi
6: Accumulation of sulphides	11.3	6	34	9.6	Laukunkangas, Mäntymäki, Niinimäki, Hälvälä, Oravainen, Hyvelä
7: Fractionation or mobilisation of sulphides	1.7	7	6	1.7	Kylmäkoski, Stormi, Koirusvesi



Figure 159. Svecofennian intrusions classified according to OD value. The Vammala area is shown enlarged in the top-right corner.



is required and the simplest one is where sulphides segregated from the magma upstream and slightly depleted but MgO_n and olivine -rich magma entered the intrusion first. Sulphides lagged behind and were carried into the intrusion with subsequent less magnesian magma, which had experienced some olivine fractionation. In any case, Hitura demonstrates that some economic cases can be rejected in the fifth screening stage. But as predicted in chapter 11.5, they are very likely low-grade disseminated deposits where massive parts are missing, likewise in Hitura.

Kotalahti (Papunen and Koskinen 1986 and Papunen 1970, 1974, Mäkinen and Makkonen 2004) receives an *OD* value 5.002. The value of the sixth parameter, sulphide accumulation, is slightly negative, -0.035, and the target fails to pass the sixth step slightly. The highest normative sulphide contents are recorded in orthopyroxenite cumulates with a moderate MgO_n , of between 20 and 30 wt.% (Figure 161c). The Kotalahti case shows that in narrow vein-like intrusions sulphide accumulation does not necessary associate with olivine accumulation and thus within olivine cumulates.



The *OD* value of Kylmäkoski (Papunen (1985a) is 7.047 analysing correctly that target is or mobilization of sulphides is very clear in Kylmäkoski (Figure 161e).

Test with Svecofennian intrusions shows that method picks up relatively well the mined intrusions, and there is only one clear failure: the *OD* value of Hitura is too low (4.018).



Figure 161. Selected Svecofennian intrusion, **a**) Hitura Co# vs. MgO_n of samples included in the calculation of parameter 5, coeval primitiveness (Ni<0.5, Cu<0.5, Sulphides>0.3% and MgO_n>10%). The positive trend and highly negative (-1.78) value leads to failing the fifth criterion and the OD value of Hitura is 4.018. The field of ore samples is delineated with field. **b**) Co# vs. Ni# of Hitura. Field shows the field of ore samples. **c**) Kotalahti. Sulphides vs. MgO_n shows that the highest normative sulphide content is met within cumulates moderate in MgO_n (20-30 wt.%). Field shows the field of ore samples. **d**) Co# vs. Ni# of Kotalahti. **e**) Co# vs. Ni# of Kylmäkoski showing fractionation/mobilisation trend of sulphides.

fertile and several samples derive close to the ore. The Co# vs. Ni# trend produced by fractionation

The technique described in chapter 13.2 gives at least a moderate estimation of the Ni and Cu tenor in the Svecofennian intrusions (Figure 162). The estimate for Cu is more reliable than that for Ni.



Figure 162. Actual <u>a)</u> Ni and <u>b</u> Cu tenor against forecasted values. Actual values are based on averages of samples with Ni>0.5% or Cu>0.5%. The forecast is based on technique described in chapter 13.2.

14.4 Thompson nickel belt

The Thompson nickel belt is a north-easterly trending tectonic mobile belt that lies on the boundary between the Churchill and Superior Provinces of the Canadian Shield in north-central Manitoba, Canada (Paktunc 1984, Peredery 1979, Peredery et al. 1982). Nickel deposits are associated with ultramafic sills that intruded at various levels within the Archean basement and within and a uniformably overlying, Early Proterozoic cover sequence known as the Ospwagan group (Bleeker 1991a, Bleeker 1991b, Cumming et al. 1982). Manibridge (Coats et al. 1976), Pipe Open Pit, Pipe No.2, Soab North and Soab South have been mined in the past. Thompson, Birchtree and T-3 mines are still in operation.

In terms of nickel exploration, the Thompson belt has certain similarities to the Svecofennian nickel belts in Finland. The targets are relatively small and mostly ultramafic. Geophysical methods have been used to locate the target, but due to poor exposure conditions sampling is costly and all methods that can give estimates on the prospectivity of the target in an early stage of operation are valuable. The purpose of the test with Thompson belt data is to demonstrate, whether the method developed works in different geological environment or is there a need to finetune the parameters location-wise.

The data from the Thompson nickel belt derives from the study of Burnham et al. (1998) including a total of 1207 analyses from 31 targets (originally the data has been largely compiled by Larry Hulbert, Geological Survey of Canada). The mines mentioned above are referred to as fertile. The bodies that host subeconomic nickel sulphide occurrences include Bowden Lake (50 Mt, @0.61% Ni), Bucko Lake (2.5 Mt, @2.23% Ni, Good and Naldrett 1993), Ospwagan Lake, Mystery Lake, Moak Lake, Hambone and Nichols Lake. Barren targets include both ultramafic cumulate bodies and metamorphosed lavas.

The vast majority of the samples are (normative) olivine cumulates with more than $30\% MgO_n$ (Figure 163a), and all the targets pass the first primitiveness criterion. The degree of sulphide saturation is low in most of the barren targets and they fail to pass the second step

(Figure 163b). None of the targets drop in the third stage of discrimination, thus the base-metal depleted targets are practically absent in the Thompson belt dataset. The barren Ospwagan volcanics near Pipe 2 all have Co#>10, but the degree of sulphide saturation is low, ca. 20 (Figure 163b). Depleted samples exist in the subeconomic Ospwagan Lake intrusion and in the fertile Birchtree, Pipe 1 and Thompson.

The majority of the remaining barren targets fail to pass the fourth discrimination step, partly because of too few samples to calculate the value of the parameter, but the samples also indicate that sulphides have not equilibrated with a large amount of magma. In the fertile Pipe 1, the Co# increases together with MgO_n , which results in screening out in the fourth step, which tests whether primitiveness is coeval. The accumulation of sulphides can be recorded in ten targets that receive an *OD* value of 6, while five targets fail to pass the criterion and their *OD* value is 5 (Figure 163c).

The fertility analysis succeeds relatively well in discriminating fertile and barren targets (Figure 163c). Fertile Soab Lake is an exception with OD value of 1; target fails to pass the degree of sulphide saturation only subtly (Figure 163b). The *OD* value of Pipe 1 is 4, which is low for a





Figure 163. Thompson Belt. <u>a)</u> Al₂O₃_n vs. MgO_n showing that vast majority of the Thompson belt samples are (normative) olivine cumulates with MgO_n%>28. Samples containing Cu<0.5% and Ni<0.5%. <u>b</u>) Depletion vs. sulphide saturation parameter. Most of the barren targets have low sulphide-saturation degree and do not pass the second criterion. Lines show the threshold values. <u>c</u>) OD value of the Thompson belt targets. White bar colour refers to barren, grey to subeconomic and black to fertile targets.

fertile target. The Co# vs. MgO_n relationship of Pipe resembles that of Rörmyrberget. The high OD value, 6, of the barren Nichols Lake b, is an interesting observation.

The Ni# of the Thompson belt intrusions is high, commonly around 95, and its variation is

small, also in the ores. These indicate that the magma has been primitive, komatiitic-picritic, and the fractionation and mobilisation of sulphides minor, as was also concluded by Coats et al. (1976) in their study on Manibridge.

14.5 Cape Smith belt

The Cape Smith Fold Belt is а paleoproterozoic volcano-sedimentary fold and thrust belt in northern Quebec, Canada (Parrish 1989). The Ni-Cu sulphide deposits occur at two different stratigraphic levels: the Raglan horizon, which occurs at the contact between the Povungnituk and Chukotat Groups, and the Delta horizon, which occurs within the Povungnituk Group. The mineralisations of the Delta horizon are associated with mafic and ultramafic intrusions, which cut the Povungnituk Group.

The nickel deposits of the Cape Smith belt are komatiitic. The purpose of the test with the data from the Cape Smith belt is to find out whether the applied method could be used in a komatiitic environment. The data from the Cape Smith belt is from the study of Burnham et al. (1998) including a total of 287 samples from 27 targets. The targets are divided according to their relationship to the Ni-Cu ores into mineralised and non-mineralised environments. All the samples contain less than 0.5% nickel and copper.

The degree of sulphide saturation divides the targets into two groups. All the targets from the non-mineralised environments are poor in sulphides, and the degree of saturation, i.e. the percentage of sulphide-saturated cumulates, varies from 0 to 44%. They fail to pass the second criterion resulting in an *OD* value of one. The targets from mineralised environments pass the



Figure 164. OD values of the targets from the Cape Smith belt. The targets with white bar are from unmineralised environment whereas those with a grey bar are from a mineralised environment.

second step with two exceptions: Donaldson East and Expo Ungava, where the OD value is also 1. The OD values of the targets from mineralised environment range from 3 to 6 (Figure 164). The OD value of mineralised West of Donaldson fails to pass the fourth step due to too few samples. Two mineralised targets fail in the fifth step, i.e. the primitiveness of sulphides and the silicates is not coeval, but the majority, 6 of 11, of the mineralised targets obtain an OD value of 6.

Figure 165 shows that the targets of non-



mineralised environment are not only poor in sulphides but also slightly base metal depleted compared to targets from the mineralised environment. The threshold value of parameter 3, undepleted magma, could be in the Cape Smith belt around 5.5, slightly lower than in the Svecofennian intrusions. This implies that the application of the discrimination tree properly in different geological environments requires finetuning.

Figure 165. Value of discrimination parameter 3, undepleted magma, versus 2, sulphide saturation, Cape Smith belt targets. The passing of the second step requires 50% sulphide saturation and third step 10% undepleted magma. Targets from unmineralised environment are screened out on the basis of sulphide saturation, but they are also slightly base metal depleted compared to targets from mineralised environment. The value of "undepleted magma" it the non-outlier minimum of the Co# of cumulates with MgO n>10 and cumulus sulphides (>0.3%).

14.6 World-class Ni-Cu deposits

Whole-rock analyses from Noril'sk-Talnakh in Russia, Jinchuan in China, Pechenga in Russia, Perseverance in Australia, Sudbury in Canada, Duluth in USA and Voisey's Bay in Canada, were collected and treated in order to find out how world-class Ni-Cu (PGE) deposits behave in the discrimination procedure developed here. Only a few analyses of these deposits include both sulphur and cobalt assays and hence the number of samples included in the test is in many cases too few and derived close to the ore. Therefore the test is neither representative nor comprehensive, but it offers a basis to discuss certain features of world-class Ni deposits in relation to the fertility analysis developed.

The world-class deposits tested can be divided into two groups according to main lithology: Pechenga, Jinchuan and Perseverance are composed mainly of ultramafic rocks whereas mafic rocks dominate in Noril'sk-Talnakh, Sudbury, Duluth and Voisey's Bay. In each step of the fertility analysis, a magnesium filter was used to screen out country rocks in order to ensure that the analysis was made of igneous cumulates. However, in the group of mafic worldclass deposits, the majority of rock samples contain less than 10% MgO n. The first step in the screening evaluates whether the magma has been primitive enough and whether it is likely olivine-bearing cumulates are that present somewhere within the target. The analysis studies if the non-outlier maximum of the mafic index is above 60%. The criterion of primitiveness rules out mafic world-class deposits like Sudbury, which is composed largely of quartz norites. To overcome this problem, a comparative test run was made where the MgO *n* filter and criterion of primitiveness were left out, and the results are presented in Table 39.

The Pechenga data is from the database compiled by Hanski including data from the studies of Hanski (1992), Predovskii et al. (1974), Skufin (1980),Golubev et al. (1984),Kremenetskii and Ovchinnikov (1986).Rabinovits (1978), Rusanov (1981), Sharkov and Smolkin (1989), Skufin and Fedotov (1989) and Smolkin (1985). The majority of the samples, 141 of 183, are picritic lavas with MgO n<20%. A total of 134 samples are included in the analysis after filtering off the samples with MgO n<10%, Cu>0.5% and Ni>0.5% (Figure 166a).

The value of the primitiveness parameter of Pechenga is 92%, and the target passes the first criterion clearly. Sulphide saturation is common but not a universal feature in Pechenga, since only 65% of samples indicate sulphide saturation but it is enough for passing the second criterion. The low Co#, between 5 and 10, indicate that a large amount of Pechenga samples are undepleted in base metals. The ore samples display a low Co# and barren samples form a linear trend showing a Co# increase from 6.5 up to 21 as the Ni# decreases from 94 to 30 as shown Figure 148b. The trend indicates fractionation of sulphides with olivine. Co# does not have a decreasing trend with increasing general normative sulphide content as required in the fourth step (Figure 148c). The value of the fourth parameter is slightly negative and the step is just passed (-0.6 vs. the threshold -1.0). Decreasing Co# with an increasing MgO *n* proves the coeval primitiveness (step 5, Figure 166d) and a positive correlation between the sulphide and MgO ncontent indicates the accumulation of sulphides (step 6, Figure 166e). No samples pass the seventh step due to tight filtering, and therefore the OD value of the Pechenga is 6.003 (Table 39). Auxiliary parameters classify Pechenga as a target, which is mainly mafic including also ultramafic part(s), which has crystallised from basaltic magma, where olivine is present as cumulus mineral.

Jinchuan in China, with reserves of more than 500 million metric tons of ore at 1.06 wt.% Ni, is one of the largest Ni deposits in the world (Naldrett 1999). The Jinchuan intrusion

Table 39 Results of the fertility analysis, world-class nickel deposits.

	Pechenga	Jinchuan	Perseverance	Duluth	Sudbury	Talnakh	Voisey's Bay
Samples (with ore samples)	174 (183)	14 (24)	44 (57)	268 (275)	33 (35)	43 (54)	6(7)
1_Primitiveness	92.1	96.5	95.6	95.6	40.9	70.7	40.5
2_Sulphide_saturation%	64.8	100.0	64.3	54.1	51.5	65.1	83.3
3_Undepleted_magma	6.2	4.8	2.1	2.1	2.0	2.1	3.8
4_Magmatic_sulphides	-0.6	2.7	2.1	4.3	3.4	7.9	2.0
5_Coeval primitiveness	1.1	2.0	0.6	-0.9	-0.4	7.9	0.0
6_Sulphide accumulation	0.5	0.1	-0.2	1.0	0.4	-0.2	-2.2
7_Sulphide fractionation			3.9	29.9	11.2	19.0	
OD	6.003	6.001	5.008	6.005	0.000	6.015	0.000
OD*	6.003	6.001	5.008	1.220	6.002	5.044	5.005
Intrusion type	MAF (21)	UM (8)	MAF (14)	MAF (42)	MAF (47)	MAF (48)	MAF (56)
The most primitive cumulate	-oC (48)	oAC (93)	oMC (76)	oOC (71)	- (0)	-oC (48)	-oC (46)
Dominant pyroxene	Opx (55)	Opx (79)	Opx (57)	Cpx (0)	Opx (84)	Cpx (36)	Cpx (0)
Parental magma	BAS (85)	BAS (85)	KOM (93)	BAS (77)		BAS (81)	BAS (80)

*MgO_n filter and step 1 excluded

212 Geological Survey of Finland Bulletin 402 Pertti Lamberg





Figure 166. Pechenga samples. a) MgO_n vs. Al₂O₃_n. b) Co# versus Ni# of samples with cumulus sulphides (>0.3%). Ore samples have low Co#. In barren samples an increase in Co# as Ni# decreases indicates fractionation of sulphides together with olivine. The line is fitted through barren samples. c) Co# generally decreases as the normative sulphide content increases indicating that sulphides are magmatic and have equilibrated with magma. Due to some high Co# in around 1% of sulphides, the value of the discrimination parameter is -0.6, and Pechenga just passes the fourth step. Vertical line shows the median of sulphides%. Only samples with MgO_n>10%, Cu<0.5%, Ni<0.5% and cumulus sulphides (>0.3%) are shown. d) Test of coeval primitiveness: the Co# decreases as MgO n increases indicating coeval primitiveness and Pechenga passes the fourth criterion. Line shows the MgO n median. Samples shown as in Figure c. e) Normative sulphide content is higher in MgO_n-richer samples. Samples with MgO_n>10%, Cu<0.5% and Ni<0.5%.

comprises dunite, lherzolite, olivine websterite and websterite (Chai and Naldrett 1992a, 1992b, Zhou et al. 2002, Zhang et al. 2002). A large part of the intrusion is mineralised and dunite, which is the principal host to sulphides, is totally of ore grade. Analyses derive from Chai and Naldrett (1992a) and from the files of Outokumpu. The data used in the fertility analysis consists of olivine cumulates and ten out of 24 samples are ore samples, i.e. Ni>0.5% or Cu>0.5%, which are excluded in the calculation of the discrimination parameters (Table 39). As shown in Table 39 all the samples indicate sulphide saturation. sulphides are undepleted, their compositions prove the equilibration with a relatively large amount of magma, primitiveness is coeval and the normative sulphide content increases as the MgO n content increases, which indicates an accumulation of sulphides. Therefore, the OD value calculated for the Jinchuan samples is 6. Auxiliary parameters classify Jinchuan as an ultramafic target, where the most primitive olivine cumulate is adcumulate. where orthopyroxene is the dominating normative pyroxene and the parental magma of which has been basaltic.

Komatiite-hosted nickel deposits are important nickel sources especially in Western Australia. The Perseverance nickel sulphide deposit is one of the world's largest single accumulations of Fe-Ni sulphides hosted by komatiites (Barnes et al. 1988 and 1995). The Perseverance and the neighbouring Rocky's Reward nickel deposits are associated with metamorphosed komatiitic olivine cumulates erupted and accumulated onto a substrate of felsic crystal tuffs. The whole-rock analyses used here are from Barnes et al. (1995). Samples derive from the A-zones of komatiite flows from four different locations: Perseverance Ultramafic North (PU North), PU South (PU South), Perseverance mineralised flow (PMF), Perseverance basal flow (PBF) and Rocky's Reward mineralised flow (RRF, Figure 167 and Barnes et al. 1995) The two first mentioned represent barren flows; mineralised flows (PMF, RRMF) are the flows hosting the sulphides and

Perseverance basal flow is the flow beneath the mineralised flow. According to Barnes et al. (1996), the mineralised flows are LREE-enriched and PGE- depleted compared to the unmineralised ones (Figure 12 in Barnes et al. 1996). PGE depletion can be identified only in the ore samples, which prevents its use as a nickel sulphide exploration tool. LREE enrichment is ubiquitous, and would lead to a correct identification if ore samples were excluded.

In the fertility analysis, the Perseverance komatiitic targets pass the first step easily, but second one is not so clear: 64% of the samples indicate sulphide saturation. Steps three to five testing the Co# itself and its relation to MgO nand normative sulphide content - show that the sulphides are not depleted in base metals, they are magmatic and equilibrated with a fairly large amount of magma and sulphide primitiveness is coeval with a high MgO n content of the host rock. The Co# is in general very low, 2-5, but the range is greater in mineralised flows than in the Perseverance basal flow. The normative sulphide content generally increases along with MgO n content as shown in Figure 167c, but due to sulphide-rich samples of Rocky's Reward, the of the parameter "sulphide value six, accumulation" is negative, thus indicating a reverse relationship between the sulphides and MgO n. Therefore, Perseverance does not pass step six, and the OD value is 5 for the whole data set.

The order of the Perseverance area targets is in decreasing OD value: Perseverance 1) mineralised flow (OD=6.007),2) Rocky's Reward's mineralised flow (5.006),3) Perseverance basal flow (3.397), 4) PU North (2.000) and 5) PU South (1.405) (Figure 167d). Only about one third of the samples from PU South are sulphide-saturated, resulting in OD value of 1. Half of the samples from PU North are sulphide-saturated, but the number of samples is too few for depletion analysis. The Perserverance basal flow also fails to pass the fourth step because of too few samples. At the Rocky's Reward flow, the amount of sulphides does not

increase with the MgO_n content, and therefore it fails to pass the sixth step and its OD value is 5. The Perseverance mineralised flow passes all but the last step, i.e. the fractionation of sulphides, and its OD value is 6. Auxiliary parameters classify Perseverance as correctly formed from komatiitic magma, but due high $Al_2O_3_n$ and normative plagioclase content, the target is classified as mafic. The most ultramafic samples are olivine mesocumulates and pyroxenes are almost equally abundant. Normative more clinopyroxene is abundant in the mineralised flows normative whereas orthopyroxene dominates the barren flows.

Testing with the komatiitic data from Perseverance shows that at least basically the



Figure 167 Perseverance data. **a**) Al_2O_3 n vs. MgO_n diagram illustrates the chemical composition of samples used in fertility analysis. **b**) Low Co# values in the Co# vs. Ni# show undepleted nature of the Perseverance targets. In the mineralised flows (PMF, RRF), Co# is more variable indicating removal of sulphides and local base metal depletion. **c**) Normative sulphide content increases against MgO_n and indicates sulphide accumulation in PU South and Perseverance mineralised flow. This feature is not visible in samples from the Rocky's Reward flow; hence the Perseverance sample set as a whole passes the "sulphide accumulation" criterion. **d**) The results of the fertility analysis of the Perseverance Basal Flow (PBF), Rocky's Reward's Flow (RRF) and the Perseverance Mineralised Flow (PMF). The first two are barren whereas the two last mentioned are fertile and PBF is the flow beneath the fertile Perseverance flow.

routine developed works with komatiites. The number of samples from the PU North and Perseverance barren flow (PBF) restricts a full analysis, but in any case the barren PU South obtains a significantly lower *OD* value than the fertile Rocky's Reward flow (RRF) and the Perseverance Mineralised flow (PMF). Sulphide saturation is a ubiquitous feature in Perseverance and a sulphide accumulation can be recorded at the Perseverance mineralised flow (PMF).

The Duluth complex is a composite, tholeiitic mafic intrusion of Mesoproterozoic age (1.1 Ga, Keweenawan) that was emplaced into the comagmatic North Shore Volcanic Group flood basalts. It consists of multiple intrusions that cover an area of approximately 4700km², making it one of the largest layered mafic intrusions in the world. It is also one of the largest Ni reserves and contains PGE and substantial amounts of Cumineralised rocks including in excess of 4000 Mt at 0.66% Cu and 0.20% Ni. However, its mineralisation is subeconomic due to its largely discontinuous, disseminated character.

The Duluth data used in this study is from the Partridge River intrusion (Severson and Hauck 1990, Komppa 1998), Dunka Road Cu-Ni deposit (Rao and Ripley 1983) and Water Hen intrusion (Strommer et al. 1990) and a sample set of several targets (referred here as unknown, Kaukonen pers.comm.). The MgO n content is above 10% in only 15% of samples with the maximum at 27.1% MgO n (Figure 168a). Due to the high magnetite and ilmenite content in several samples the mafic index is high, and Duluth passes the first criterion regardless of whether MgO n filter is used or not. The second step of sulphide saturation is critical to the data used in this analysis. In general, the normative sulphide content of the Duluth rocks is relatively low, 0.7%, and only about 30% of the samples indicate crystallisation from sulphide-saturated magma, i.e. sulphides occur as cumulus phase (>0.30%). Sulphides are much more abundant and common

in MgO n-rich samples, and the degree of sulphide saturation is 54% of the samples with MgO n>10%. The samples with MgO n>10 also pass the fourth ("undepleted magma"), the fifth ("coeval primitiveness") and the sixth ("sulphide accumulation") criteria. The OD value of the Duluth is 6.005 if the analysis is made for samples with MgO n>10%, but only 1.220 if all samples are included. According to the auxiliary parameters, Duluth is a mafic intrusion containing olivine-bearing cumulates, clinopyroxene is the predominant normative pyroxene and the parental magma has been basaltic and relatively evolved compared to the world-class deposits discussed above. Of the separate intrusions, Water Hen displays the highest OD, 6.005, while the others have values below 4.

The Noril'sk, Talnakh and Kharaelakh intrusions of the Noril'sk district in the extreme north-western corner of the Siberian platform host outstanding Ni-Cu and PGE resources. The application of the fertility analysis in the Talnakh intrusion was studied using the data of Czamanske et al. (1995) including a total of 54 whole-rock analyses from two drill holes. The OD value of the Talnakh intrusion is 6.015, but its high value is mainly due to samples from the lower part of the intrusion. Samples of the Talnakh intrusion are divided here into three groups according to stratigraphy, mineralogy and chemistry, as illustrated in Figure 169. The lowermost part comprises picritic, taxitic and contact gabbrodolerite. The middle part consists of olivine and olivine-bearing gabbrodolerite. The rock types of the uppermost part include quartz diorite, magnetite gabbro and prismatic gabbro. The lowermost part hosts the Ni-Cu-PGE ore. The MgO *n* content decreases from 30% in the lowermost part via 16% in the middle part to as low as 1% in the upper part. Only the lowermost part passes the first criterion of the fertility analysis (Table 40).


Sulphide saturation is common but not a uniform feature in Talnakh, as illustrated in Figure 169 (Table 3 in Czamanske et al. 1995). The degree of sulphide saturation is high in the lowermost part (100%) and in the uppermost part (86%), but it is low to moderate in the middle part, which does not pass the second criterion. The degree of base metal depletion varies widely in Talnakh, as shown by Co# *vs.* Ni# graph in Figure 169. The lowermost part and the ore display a very low Co#, 1-2, but in the uppermost part the Co# is around 10. Co# indicates that the lowermost part is very primitive in terms of base metal undepletion, whereas the uppermost part has experienced a significant removal of olivine



Figure 168. Duluth.

<u>a)</u> $Al_2O_3_n vs.$ MgO_n-diagram indicates that in most of the samples MgO_n content is below 10%. The result of the analysis is totally different, if the MgO_n>10 filter is ON (OD = 6.005 vs. 1.220).

b) Sulphides *vs.* MgO_n. Duluth passes the second step, sulphide saturation, if only samples with MgO_n>10 are included. Otherwise the OD value of Duluth is 1.220. Horizontal line with MgO_n=10% shows the position of the filter.

<u>c)</u> Co# vs. Ni# of samples with cumulus sulphides (>0.3%). Co# is very low, mainly between 0.3 and 3, although the Ni# is relatively low. This indicates that significant amounts of sulphides have not been removed.

and sulphides in comparison to the lowermost part.

The uppermost part does not pass the fourth criterion that indicates large-scale equilibration with magma. On the contrary, the lowermost part passes criteria from four to six. Although fractionation of sulphides is a well-known feature in Noril'sk and Talnak, the data from Talnakh does not imply that and the seventh criterion is not passed.

The Talnakh case shows that a target may consists of different parts giving dramatically different *OD* value as given in Table 40. The middle and the uppermost part do not pass the first criterion of primitiveness. If the first stage is



omitted, the middle part does not pass the second criterion either. Omitting the first criterion, the upper layer receives an *OD* value of 3. If the magnesium filter and the first step were omitted in the fertility analysis, the *OD* value of Talnakh, as a whole, would be 6 (Table 39). The Voisey's Bay world-class massive Ni-Cu sulphide deposit was discovered in 1993. It is the only known economic deposit associated with troctolitic intrusion in an anorthosite-troctolite-gabbroferrodiorite igneous suite (Naldrett 2000, Coates and Mitchell 2000, Ryan 2000). Intrusions in the northern Labrador have been divided into four



Figure 169. The Talnakh intrusion.

a) Al₂O₃_n vs. MgO_n. Note the low MgO_n in the middle (Go/Gob) and upper part (D/Dm/Dq/Dk) of Talnakh.

b) Normative sulphide content *vs.* MgO_n. Normative sulphide content is high in the lowermost part but low in the middle part.

C) Co# vs. Ni# showing very primitive, non-depleted, nature of the lowermost part. If all the parts are cogenetic, significant amounts of olivine and sulphides have been removed before the formation of the uppermost part, since its Co# is high compared to the lowermost part. D=Prismatic gabbro, Dm=magnetite gabbro, Dq=quartz diorite, Go=olivine gabbrodolerite, Gob=olivine-bearing gabbrodolerite, Gp=picritic gabbrodolerite, Gk=contact gabbrodolerite, Gt=taxitic gabbrodolerite.

types according to main lithology: 1) pyroxenitic, 2) anorthositic, 3) ferrodioritic and 4) gabbrotroctolite intrusions. The last group is the most prospective due to its relatively unevolved parental magma resulting in the highest nickel contents (Kerr and Ryan 2000). Voisey's Bay is the only Ni-Cu deposit of economic significance in the area.

The data of the Voisey's Bay from Li et al. (2000) contains only seven averages of different rock types and one is of ore grade. The number of samples is too few for a proper fertility analysis. The Voisey's Bay intrusion consists mainly

for the analysis from Czamansk	te et al. 1995.					
Zone	Quartz diorite		Olivine gabbronorite		Picritic, taxitic and contact gabbrodolerite	
	$MgO_n > 10$	All	$MgO_n > 10$	All	$MgO_n > 10$	All
OD	0.000	0.000	0.000	0.000	6.004	6.007
OD (step 1 excluded)	0.000	3.125	0.000	0.000	6.004	6.007
1 Primitiveness		59.6	42.3	47.9	74.9	74.9
2 Sulphide saturation %		86.7	42.9	31.6	100.0	100.0
3 Undepleted magma		7.5	4.7	4.7	2.1	2.1
4 Magmatic sulphides		-1.4		8.5	3.8	2.2
5 Coeval primitiveness		21.1		1.8	3.8	1.5
6 Sulphide accumulation		-0.7	0.0	0.0	0.8	1.5
7 Sulphide fractionation					9.3	17.1

Table 40. Fertility analysis of Talnakh intrusion; three different layers are treated separately. Ore- hosting layer of picrite gabbro would obtain a high OD value correctly, whereas other layers would obtain a OD value of zero. For each layer two different results are given. In the first analysis (MgO_n>10 %) only samples containing more than 10 % MgO_n are included, whereas in the other analysis all samples are included. In both cases, however, samples with more than 0.5 wt.% Ni or Cu are excluded. Data for the analysis from Czamanske et al. 1995.

of troctolitic and olivine gabbros the MgO ncontent of which is between 6 and 12 and the mafic index is below 50 %. The MgO n content reaches 20 % only in melatroctolite inclusions (Li et al. 2000). If a magnesium filter (MgO n>10 %) were used in the analysis, the OD value would be zero. If both magnesium filter and the primitiveness step were omitted, the OD value would be 5 (Table 39). The normative sulphide content does not increase with MgO *n* in the rock type averages, and therefore criterion 6, the accumulation of sulphides, is not passed. Sulphide saturation is not an overall feature in the Voisey's Bay, and the average sulphur content of the normal troctolite is according to Li et al. (2000) is only 0.06 wt.% S. Therefore, the passing the second step depends on the proportion of normal troctolite samples.

Sudbury is one of the world's largest and most productive mining camps with a resource of >1648 million metric tons at ca. 1.2 wt.% Ni, 1.0 wt.% Cu and 1 ppm Au+PGE's (Lesher and Thurston 2002). The Sudbury structure, Sudbury Igneous Complex (SIC) and associated Ni-Cu-PGE ores were originated from the collision of an approximately 10 km diameter bolide about 1850 Myr ago (Mungall et al. 2004). Ore deposits can be divided into three categories (Lightfoot and Farrow 2002; Naldrett 1989, 2004). 1) Deposits localised along the lower contact of the Sudbury Igneous Complex, where ores occur in depressions in thick units of inclusion-rich norite and partially melted and brecciated footwall gneisses. 2) Sublayer deposits occur in the sulphide vein stockworks within the country rock up to 1.5 km away from the contact with the SIC. 3) Deposits in offset dikes occur as radial and concentric discontinuous bodies around the SIC (Murphy and Spray 2002).

Because the offset dikes host almost 50 % of the mineral resources of Sudbury (Lightfoot and Farrow 2002) and their size is comparable with deposits of types 1 and 2, the Worthington offset dike was selected in the fertility analysis test to represent Sudbury. Data is from the study of Lightfoot and Farrow (2002) including a total of 29 whole-rock analyses.

The rock types of the Sudbury Igneous Complex including the offset dikes are norites, quartz gabbros and quartz norites, the MgO_n contents of which are mainly below 10 %. If the primitiveness step and MgO_n filter were included in the tests, the OD value of the Worthington offset dike would be zero as shown in Table 39. Without the magnesium filter and primitiveness criterion the Worthington offset dike would receive an OD value of 6. Sulphide saturation is not an overall feature in the Worthington offset dike, and the second criterion is just passed, 51.5 % vs. 50 % threshold. Steps 3-6 are passed more clearly: the Co# is generally very low (Figure 170), it decreases with increasing MgO_n and normative sulphide content and sulphides are more abundant in MgO_n -rich rocks.

14.6.1 Conclusions of the test with worldclass deposits

Tests with very limited and non-representative data from world-class deposits show that the primitiveness criterion is not a relevant step in the fertility analysis and its use has to be evaluated area by area. The same is true for the MgO_n filter. Both may be good at ranking maficultramafic intrusions, but there is a danger of filtering out deposits that are largely mafic, like Voisey's Bay, Noril'sk and Sudbury.

Sulphide saturation is not a uniform feature in many rocks related to many of the world-class deposits. The case study intrusions and tested cases show clearly that sulphides are abundant within and close to the ore, but if samples are taken far away from the ore, there is the risk that sulphide saturation criterion is not passed, and the target is screened out at an early stage. For example, in Talnakh, the sulphide saturation is restricted to the lowermost part, which is practically totally mineralised. In the Noril'sk area, it is probable that the fertility analysis fails to identify completely fertile intrusions from the barren ones if only unmineralised parts are sampled. Sulphide saturation is also restricted close to the ore in other deposits rich in PGEs, such as Sudbury that is largely barren of sulphides (e.g. Thierriault et al. 2002).

The remaining steps 3-7 of the fertility analysis are based almost entirely on sulphide-bearing samples and the Co#, which requires that the sulphide occurs as a cumulus phase, i.e. the normative sulphide content must be >0.3 %, when calculated from whole-rock analyses. If steps 1 and 2 were modified in such a way that e.g. barren Sudbury samples passed onto step 3, the fertility analysis would be incapable of identifying the ore-hosting potential of the target due to the essential part played by Co# in the analysis. The fertility analysis developed here works properly only in areas, where sulphide saturation is an ordinary feature in fertile nickel exploration targets. This problem must be identified and considered when the fertility analysis is applied in areas where typical intrusions are commonly poor in sulphides.



Figure 170. Worthington offset dike, Sudbury. **a**) Al_2O_3 *n vs.* MgO_n showing that most of the rocks are norites and quartz norite-diorites. If the MgO_n filter and primitiveness criterion were included in the fertility analysis, the OD value would be zero. **b**) Co# *vs.* Ni# of samples with cumulus sulphides (>0.3%). Low Co# shows highly undepleted nature of Worthington sulphides. Relatively low Ni# indicates that silicate magma is relatively evolved.

15 APPLICATIONS IN PGE EXPLORATION

Platinum-group element (PGE) deposits and PGE exploration are out of the scope of this study, but because PGE are frequently associated with Ni-Cu deposits and are in several cases economically important, the relationship between Co# and Ni# and the occurrence of PGE is discussed briefly in the Duluth and Keivitsa intrusions on the basis of the analytical data including PGE. Duluth and Keivitsa are both currently subeconomic deposits with significant but low-grade Ni-Cu-PGE mineralisations.

15.1 Relationship between PGE and Co#

The database of the Duluth complex (Patelke et al. 2003) includes a total of 9049 samples assaved for Cu, Ni, Co, S, Pd, Pt and Au. Samples with more than 1 ppm Pd+Pt+Au (termed PGE+Au in the following) are generally rich in sulphides and nickel (Figure 171a and b). Although the correlation between abovementioned elements is moderate, the accuracy in the discrimination of samples with PGE+Au>1ppm is poor on the basis of sulphur and nickel. PGE+Au -rich (<1ppm) samples plot in the Co#-Ni# diagram in a low Co# range, 0.3-3, and variable Ni#, 10-66 (Figure 171c). PGE+Au contents display negative correlation with Co# (Figure 171d). If a Co#<1.5 is used as a rule to select samples with PGE+Au >1 ppm, more than 90 % of PGE+Au-rich samples are selected correctly. Correspondingly, the rule of Co#>1.5 to select samples with PGE+Au<0.1 ppm gives a correct result in 95 % of PGE+Aupoor samples. If samples are divided according to Co# in PGE+Au-rich and -poor groups (>1 ppm and <1ppm), the selection is correct in 65 % of samples.

The Kevitsa-Satovaara complex including the subeconomic Keivitsa Ni-Cu-PGE deposit (also called Keivitsansarvi and Kevitsa) is located 34 km north of Sodankylä in Finnish Lapland. The deposit within the ultramafic intrusion was discovered and drilled by the Geological Survey of Finland. In the studies on geology, mineralogy and petrology of the intrusion and the Ni-Cu-PGE deposit, Mutanen (1997) identified several ore types with various *Ni tenors* and PGE content. The PGE content is highest in the Ni-PGE ore

type. According to Scandinavian Gold Limited, the inferred resources are 315 million metric tonnes at 0.18 wt.% Ni, 0.29 wt.% Cu, 0.20 ppm Pt, 0.12 ppm Pd and 0.08 ppm Au (January 2005, www.scandinaviangold.com/kevitsa). PGE does not correlate with S nor with Ni and poorly with Cu (Mutanen 1997), but clearly with Co# as shown in Figure 172. Like Duluth, Keivitsa analytical data also allows the selection of PGErich samples on the basis of Co# (Lamberg et al. 2005).

In order to study the extent of anomalously low values of Co# within the PGE-rich layers, and whether there are other useful tools to locate the critical layers, drill hole M52/3714/93/R679 was studied in detail (Appendix 5 in Mutanen 1997). The almost one-km drill hole intersects several ore types in the ultramafic zone, which consists mainly of clinopyroxene and clinopyroxene-olivine cumulates with subordinate thin olivine cumulates, as indicated by the variance of MgO n content in Figure 173. According to Mutanen (1997) the younging direction in the stratigraphy is upwards, which is supported by general decreasing trend in the Ni#. The PGE content is high, >0.5 ppm, at several intervals: 750-760 m, 620-700 m, 490-600 m and 140-230 m. A high PGE coincides with high sulphide, Ni and Cu contents and especially with low Co#. A deviation from the previous cases is that the Co# here indicates the general trend and location of horizons of PGE potential with a limited amount of samples, such as 1 sample per 25 m, and from more than 100 m away.



Figure 171. Duluth, data set of Patelke et al. (2003). a) Sulphur and b) Ni show only a moderate correlation with Pt+Pd+Au. c) Co# vs Ni# of samples with cumulus sulphides (>0.3 %). Boxed area is the range of samples with >1 ppm Pt+Pd+Au. d) Correlation between Pt+Pd+Au and Co#, samples with S>0.2 % are drawn, (n=2417). PGE enrichments are related to parts with extremely low Co#. Graph is divided into six fields and the percentage of samples in each group is: A=11.2 %, B=1.2 %, C=33.4 %, D=32.2 %, E=0.9 % and F=21.2 %.

15.2 Testing of Co# as a PGE exploration tool

The coincidence observed of very low values of Co# with an elevated PGE is in harmony with the theory and model presented in chapter 3.5. Since the platinum-group elements have very high sulphide/silicate partition coefficients (Table 3), even a small removal of sulphides will deplete the magma of PGE. Therefore, the PGE ores can only form in magmatic systems, which have not suffered sulphide removal upstream. In practice, this means that sulphide saturation has taken place in the intrusion chamber or in the feeder channel. In Duluth, a relatively low and variable degree of sulphide saturation together with an extremely low Co# is an indication of specific



Figure 172. Keivitsa samples. a) Pd+Au ppm versus Co# of 15482 samples from Keivitsa. Samples are divided into two groups according to Co#=2. In the left group with Co#<2 the average Pd+Au is 0.39 ppm while in the right group the average is 0.05 ppm Pd+Au. b) Co# vs. Ni# shows the range of samples with PGE>0.5 ppm. Note the wide spread in Ni# (see text for discussion).

conditions required for PGE ore formation. In Keivitsa, the variation of Co# indicates that during the formation of the cumulus pile, the degree of PGE depletion in the magma has varied widely and partly in an unpredicted way.

PGE exploration tools, as in Ni exploration, are presumed to: 1) discriminate fertile intrusions from barren ones and 2) point to the location of the PGE ore on the basis of limited, random sample set taken away from the mineralisation. The second task is probably more important in PGE than in Ni exploration. Ni ores are commonly rich in sulphides and relatively large and therefore can be located by geophysical means. In contrast, PGE ores are low in sulphides, form narrow but continuous reefs, and are difficult to locate and follow with geophysical and geological methods. The applicability of Co# for screening the most potential targets in Duluth and layers in Keivitsa was tested using barren samples: i.e. PGE+Au<0.5 ppm, Ni<0.5 wt.% and Cu<0.5 wt.%. Targets of Duluth equal the deposits in the database of Patelke et al. (2003).

The following figures were calculated: 1) minimum Co# of the sample set, 2) primitive Ni#, i.e. the average Ni# of samples with low Co#, 3) trend measures the interdependence between Co# and Ni# and it is the slope of the trend line in the Co#-Ni# diagram. In addition, the maximum PGE content of the target was calculated using all samples.

The result of Duluth is illustrated in the bubble diagram in Figure 174, where the minimum Co# is plotted against a primitive Ni# and the size of the bubble indicates maximum PGE+Au. The minimum Co# of the barren samples correlate with the maximum PGE+Au of the target and demonstrate the most potential targets can be screened and ranked with the technique.

Figure 176 shows the PGE key figures of the layers in the drill hole M52/3714/93/R679 of Keivitsa. Layers 4, 7, 8, 9 and 15 display Co# minima in locations, which are also rich in PGE+Au. The conclusion is that the technique can point out the most potential layers in a thick cumulus pile.



Figure 173. Variation of MgO_n, sulphide, Ni, Cu, Ni#, Co# and PGE+Au content as a function of depth (metres) in an almost 1 km long drill hole M52/3714/93/R679 (Appendix 5 in Mutanen 1997).

15.3 Additional information obtained from Ni#

In Duluth, the Co# trend is positive and low values of Co# coincide with low Ni# as shown in Figure 171. As demonstrated in Chapter 3.5, the

trend of Duluth can only be explained by fractional removal of sulphides in a system where the partition coefficient of copper between the



with

are

Figure 175. Number refers to different stratigraphic layers of the Keivitsa drill hole M52/3714/93/R679 (Appendix 5 in Mutanen 1997). From left to right: PGE maximum ppm, minimum Co#, Ni# of the most primitive samples in terms of Co# and trend. The value of the trend corresponds to the slope of the sample distribution control line in Co# vs. Ni# diagram. High PGE contents in layers 7, 8, 9 and 15 coincide with low Co#, relatively low Ni# and negative trend. Values are missing in the layer 5, because too few samples passed filtering (sulphides as cumulus phase, i.e. >0.3 %; Ni<0.5 wt.%; Cu<0.5 wt.%; PGE+Au<0.5 ppm).

sulphide melt and silicate magma has been higher than that of nickel, D_{Ni}<D_{Cu}. The variation of Ni# between 10 and 30 with a low Co# can be the result of: a) fractional crystallisation of mafic silicates, mainly olivine, from the system, b) change of the Cu and Ni compositions of the magma by other means, c) change of the ratio of partition coefficients of nickel and copper. Olivine cumulates are present in Duluth, and hence the first alternative is the most probable explanation. In that case, the most primitive magma of Duluth is characterised by a low Co#, indicating that sulphides have not fractionated from the system, and a high Ni#, i.e. no olivine fractionation. Correspondingly, cumulates with low Co# and high Ni# represent the first fractions.

The most primitive target in terms of Ni# and Co# is "South Filson Cr" with Ni# ca. 30 and Co# 0.2. In comparison Ni# and Co# indicate that "Dunka Pit" formed from evolved magma, from which some olivine was fractioned. This caused a slight increase in Co#, as shown in Figure 8b (p. 29). The minimum Co# of Dunka Pit is, however, slightly lower, which indicates that although some olivine was removed, magma was more primitive in terms of sulphides. The following model explains the observed Ni#-Co# variations of Duluth: 1) Sulphide undersaturated Ni, Cu and PGE-rich magma ascents into crust. 2) Fractional crystallisation of olivine starts in the feeding channel. 3) Magma intrudes in several stages into the Duluth magma chamber, i.e. current intrusion. The degree of fractionation in terms of olivine varies. 4) Crustal contamination in the feeder introduces sulphur in the magma. Contaminated magmas become sulphur-saturated and sulphides starts to fractionate. 6) PGE-rich portions of the Duluth complex represent the cumulates that formed while the first sulphides fractionated. The

degree of olivine fractionation in PGE-rich portions varied from low (South Filson Cr) and moderate (Dunka Pit) to high (H1C/Anorth "pillar"). Most of the PGE-rich targets formed from the magma, from which some olivine was fractionated, e.g. Birch Lake, Babbit and Dunka Road. 7) Fractionation of sulphides depleted the magma in PGE and the subsequent cumulates are poor in PGE and display a higher Co#. Since the range of Co# is significant, extending up to 30 (Figure 171) and the trend is positive and steep, the total amount of fractionated sulphides is considerable, when also compared to the amount of fractionated olivine (Figure 10c).

Keivitsa shows a more complicated variation in Co# and Ni# (Figure 172b, Figure 173, and Figure 175). Figure 176 shows the most primitive cumulate in terms of Co# and the trends of the layers in Co#-Ni# diagram. In layers 1-3 and 5 Ni# is high and the Co# trend is negative, whereas in other layers the Ni# is much lower and the trend is positive. Layer 14 is an exception with a high Co# and negative trend. Changes in the Co# trend from negative to positive and the shift of Ni# cannot be explained by differences in the ratios of fractionating olivine and sulphides only, but require at least a change in Cu to Ni ratio of the magma and possibly change in the partition coefficient from D_{Cu}<D_{Ni} to D_{Ni}<D_{Cu}. According to Mutanen (1997) the peculiar features of chalcophile and siderophile elements originate from the mixing of sedimentary material with a komatiitic one. If his model were adopted here, layers 1, 2, 3 and 5 would be close to the komatiitic end member, whereas the sedimentary material would dominate the other layers. This shows that the use of Ni# and Co# together can give valuable information about changes in the composition of magma, which are very difficult to trace by other means.



Figure 176. Ni# vs. Co# diagram of the Keivitsa, layers of the drill M52/3714/93/R679 hole (Appendix 5 in Mutanen 1997). Only samples with cumulus sulphides. The circle indicates the sample with lowest Co# (PGE-rich layers with solid circle), and the general trend of other cumulates of the layer is shown with trendline. Note that the layers display two different trends: 1) Co# increases as Ni# decreases. This negative trend exists in layers 1-3, 5 and 14. 2) Co# decreases with decreasing Ni#. This positive trend is in layers 1,2 3, 5 and 14. Layer 4 is not shown.

15.4 Discussion

In Keivitsa, the high PGE contents exist in layers which display a) low Co#, b) relatively low Ni# and c) positive Co# trend. Layer 5 is an exception: the Ni# is high, 85, and the Co# trend is negative. Figure 177a shows the most important targets discussed in this study in a Co# min vs. Ni# primitive diagram. PGE ores: Talnakh, Suhanko, Sudbury and Duluth all plot in Co#<2 and Ni#<50, while nickel deposits have both higher Ni# and Co#. On the basis of this observation the targets are divided into four categories: 1) Ni ores and potential Ni deposits (Ni#>50, Co#<10, mainly Co#>2); 2) PGE ores and potential PGE deposits (Ni#<50, Co#<2); 3) barren deposits (if Ni#>50 and Co#>10 or if Ni#<50 and Co#>2).

The reason for the low Co# in PGE deposits is in the high partition coefficients of platinum group elements in sulphide melt and in the R factor. A very low Co# indicates that prior sulphide segregation has not taken place and that the R factor has been high (Figure 8a), which are both required for the formation of PGE ore. There are at least three explanations for the association of low Ni# and high PGE. (1) The first is fractionation of sulphide magma, which results in sulphide ores that are rich in Cu, Pt, Pd and Au and relatively poor in Ni#, Rh, Ru, Ir and Os. These ores are associated with pyrrhotite-rich ores that are depleted in Cu, Pt, Pd and Au and have a high Ni#. The mechanism has been explained in Figure 12. Sudbury and Noril'sk are examples of this style of mineralisation.

The other two explanations start from the observation that a low Ni# indicates that magma has been moderate or low in MgO (cf. Figure 6, p. 26). There are two ways to reach high PGE content in the parental magma: high degree of melting of the mantle to remove all sulphides, and two-stage melting of the mantle. A high degree of melting produces high MgO melts like komatiites with a high Ni#. (2) According to the second explanation, fractionation of olivine brings the Ni# down and if sulphide saturation takes place late, magma and corresponding mineralisation will be low in Ni# and high in PGE. Naldrett

(2004) has called this "delayed separation of sulphide during the crystallisation" and this mechanism gives rise to deposits that are relatively rich in Cu, Pt, Pd and Au and low in Ni. Examples of this type of mineralisation occur in Bushveld, Kaergaard, Sonju Lake and Rincon del Tigre (Prendergast et al. 1998). (3) The third explanation is that PGE-rich and moderate to poor Ni# magmas are the result of the two-stage melting of mantle, where in the first stage a small amount of sulphides are left in the mantle and they are taken into the melt along with the PGE during the second stage of melting (Naldrett 2004, Hamlyn and Keays 1985, Nielsen and Brooks 1995).

Potentially the association of a low Ni#, <50, with a very low Co#, <2, is either an indication of a PGE-rich melt that has experienced sulphide segregation with a high R, or that a sulphide melt has fractionated.

Co# and Ni# display positive relationships in PGE deposits: Sudbury (Figure 170b), Noril'sk (Figure 169c), Duluth (Figure 168, Figure 171), in main part of Keivitsa (Figure 176) and Suhanko (not shown). A positive trend means that D_{Ni}<D_{Cu}, which seems to be the case in MgOpoor magmas, while a negative trend and D_{Cu}<D_{Ni} seem to prevail in komatiites and in other high MgO melts. Although the change in the partition coefficients with a decreasing MgO content of magma is opposite to that given by Naldrett (1989), most of the values from literature shown in Figure 7 (p. 28) are in harmony with observations of this study. Figure 177b shows the trend vs. Ni# primitive of Svecofennian intrusions. Data scatters, but the general trend indicates predominantly positive values when the Ni# is below 60, whereas a negative trend is more common in targets with Ni# primitive is >60.



Figure 177 **a)** Case study targets, world-class deposits and some other selected deposits shown in Co# min versus Ni# primitive – diagram. Field for PGE deposits and Ni deposits shown. SMUI: Svecofennian mafic-ultramafic intrusions, TNIB: Thompson Ni belt intrusions. **b)** Co# vs. Ni# trend versus Ni# primitive, Svecofennian mafic-ultramafic intrusions of Finland. Targets with more than 10 samples. Fitted line shown.

15.5 Discrimination of PGE potential intrusions

Based on the observations discussed above, the following criteria were set for PGE potential targets: a) intrusion type is mafic, b) in case of a

large layered intrusion the orthopyroxene should be the predominant normative pyroxene, c) the degree of sulphide saturation should be preferentially relatively low, <70 %, <50 %; a high degree of sulphide saturation increases the risk that some sulphides have lagged behind and depleted the magma in PGE, d) Ni# should be relatively low, <50, e) Co# trend should be positive, i.e. as Ni# decreases the Co# decreases, and f) Co# should be extremely low, <2.

Based on requirements e) and f), Svecofennian intrusions were classified and *OD/PGE* value was calculated as shown in Figure 178. The decision tree proposed is simple and only tentative. The step of Co# trend is not necessary, because most of the targets with Ni#<50 will anyway fill this criteria. The step is only included to screen out targets, where the Ni# and Co# trend are not in harmony, which is mainly due to some outliers in small data or scattering of the data (e.g. Forssa in Figure 179).

The *OD/PGE* value of the Svecofennian mafic-ultramafic intrusions was calculated from the *NIXPLOR* database of Outokumpu Oyj (Figure 179). All Ni-Cu deposits are depleted in PGE, and therefore the expectation is that none or very few targets will get an *OD/PGE* value >3. As shown in Figure 179, seven targets out of 112, i.e. 6.3 %, plot in a field of "PGE potential intrusions". Oravainen is located on the west coast of Finland near Vaasa. The geology and mineral deposit was described by Isohanni (1985) and he states that the resources of nickel and copper are 1.3 Mt of ore at 0.95 wt.% Ni and 0.16 wt.% Cu, but the PGE content reported by Papunen (1989) have been analysed in samples

with Ni#>50 and are low. Three other PGE potential targets Honkola, Leineperi and Suvitie have been drilled, but the results are not known. Three unlabelled are unknown targets with an ID number only on the database.

There are some targets in the field of "Ni potential intrusions" with a very low Co#, <2, Koivakkala Joutsenmäkinamely and Tolvanniemi (Parkkinen 1975). The rule to screen out all the intrusions with Ni#>50 in the first stage is based on a quick analysis of deposits shown in Figure 177. The lower the Co#, the higher the PGE content of the Ni deposits should be, within a deposit type, i.e. komatiitic, picritic, basaltic deposits. Of the Svecofennian intrusions, the highest PGE contents have been recorded in Ekojoki, which has a low Co# min, but in Koivakkala and Joutsenmäki-Tolvanniemi the Co# min is even lower, and therefore they would deserve PGE analyses.



Figure 178. Decision tree in calculation of the Overall Discrimination index for PGE exploration, OD/PGE.

16 DISCUSSION

16.1 Are the sample sets biased?

In nickel exploration, the lithogeochemical tools should indicate the fertility of the intrusion from barren samples, which derive far away from the ore itself. In this study, the ore samples were excluded with filters Cu<0.5 wt.% and Ni<0.5

wt.%. The filtering, however, was incapable to exclude low-grade samples close to or within the ore from the data sets. This may have biased both the development of the methodology and testing and consequently showing too positive result.





The test with sample reduction in chapter 13.1 showed that method is not very sensitive in sample reduction when samples are picked randomly or if MgO_n -rich samples are included. However, when an analysis is based on MgO_n -poor samples, the accuracy decreases especially in the gabbroic intrusions of Laukunkangas and Bruvann.

Method calls for a more critical and betterprepared test, where the effect of ore proximity

16.2 Comparison to earlier studies

There are few extensive comparative lithogeochemical studies of barren and fertile Ni sulphide exploration targets. Most studies have concentrated on one methodology only and the number of targets has been low. Exact criteria of decision are practically non-existent as are validation and testing. Below. the most comprehensive work done in Finland, Canada and Australia is reviewed, discussed and compared to the results of this study.

could be qualified in a more unambiguous way. However, tests with Råna intrusion and Svecofennian targets imply that the bias may not be significant. In the Råna intrusion, the *OD* value was 5-6 in a large area of the intrusion (chapter 13.2). In the Svecofennian test, the *OD* value does not correlate with the highest Ni, Cu or S contents of the targets. Four of the six intrusions with the highest possible *OD* value are not known to be highly mineralised.

In Finland, Outokumpu collected an extensive database of mafic-ultramafic intrusions of Svecofennides in the Nickel Programme mainly in the 1960s and 1970s (Häkli 1963, 1966, 1970, 1971, see the compilation of unpublished reports by Hautala 1982). The decision-making was essentially based on the Ni content of mafic silicates which was found to correlate with the Ni content of sulphides and was initially used in estimating the Ni tenor of the deposit based on

barren cumulates (Häkli 1963, 1971) and in localising the earliest fractionates of the differentiation series (Häkli and Wright 1967, Häkli 1968, 1971). This work and the discoveries of Hitura and Kotalahti Ni deposits directed the exploration to two favourable belts, the Hitura-Kotalahti-Laukunkangas-Parikkala and the Ahlainen-Vammala-Kylmäkoski. Within the belts the intrusions with high Ni content in mafic silicates were regarded as those with the most potential and the same criterion was also used within the intrusions to locate the ore. Häkli (1970) utilised factor analysis to draw similar conclusions based on chemical assays by Leco for sulphur and nitric acid dissolution + AAS for the base metals.

Häkli (1971) found that the Ni content of mafic silicates drops considerably close to the ore in Stormi, i.e. Tyrvää, Kotalahti, Kylmäkoski and Parikkala deposits. This was termed depletion and was explained on the basis of sulphurisation after Naldrett (1965). The depletion was observed only within about 100 m from the ore (Häkli 1971). Duke and Naldrett (1978) and Duke (1979) showed by modelling that the Ni content of olivine decreases rapidly in sulphide-saturated systems from which olivine and sulphides fractionate. compared to the sulphideundersaturated case. Based on this, the model and practical use of olivine and its Ni content in exploration were established.

In Outokumpu Exploration three main rules were followed (Grundström 1982): 1) intrusions with high Ni content of olivine are the most prospective, in Svecofennian intrusions the value of about 1000 ppm was regarded as adequate, 2) a strong decrease in the Ni content of mafic silicate with a narrow Mg# indicates a high Ni sulphide ore potential, 3) within the intrusion the parts with the highest Ni content of mafic silicate are the most prospective. The application of these criteria led to the discovery of the Laukunkangas Ni-Cu ore (Grundström 1980 and 1985) and several subeconomic deposits. However, most of the discoveries like the mined nickel deposits at Telkkälä (Häkli et al. 1975, Pietilä 1991), Stormi (Häkli et al. 1979, Häkli and Vormisto 1985), and Kylmäkoski (Papunen 1980, 1985a), were made by utilising direct geological and geophysical exploration methods on the proximal sides of mineralised glacial boulders initially discovered by a layman.

A basically similar approach has been utilised successfully by the Geological Survey of Finland in the Juva and Kotalahti areas since the 1980s (Makkonen 1992, 1996; Forss et al 1999; Makkonen et al. 2003). Ca. 600 olivine analyses have been carried out from systematically collected samples (Makkonen pers. comm.). Targets with high Ni content of olivine, >1500 ppm, and wide variation within a narrow forsterite range have been ranked as the most potential (Mäkinen et al. 2002, Mäkinen and Makkonen 2004). Several Ni-Cu occurrences have been discovered, of which the most important ones are Rytky (Mäkinen and Makkonen 2004, Mäkinen et al. 2002), Särkiniemi (Kontoniemi Forss 1997), and Niinimäki (Makkonen and Forss 1995). Hanhisalo (Kontoniemi and Forss 1998), Törmälä (Kontoniemi and Forss 1999) and Mäkisalo (Kontoniemi and Forss 2001).

Presumably, the Ni content of olivine has been applied or at least tested in all the major areas of Ni exploration. In the Tabankulu and Insizwa intrusions, South Africa, Lightfoot and Naldrett (1984a and 1984b) and Lightfoot et al. (1984 and 1987) concluded on the basis of olivine composition that the Ni-poor olivines had reacted with sulphides before the magma intruding to the level covered by the sampling. According to Naldrett (2004), the location of these hypothetical sulphides has been subject to several unsuccessful exploration projects. The systematics of olivine composition have been described in the Voisey's Bay, Pants Lake, Moxie and Katahdin intrusions (Maine, USA) (Naldrett 2004).

In komatiites primary olivines are very rare, and therefore the whole-rock Ni vs. MgO has been used instead of olivine analyses as described for the first time by Naldrett and Gasparrini in 1971. In a recent review Naldrett (2004) shows that the komatiites of unmineralised sequences in the greenstone belts of Canada, Australia, Zimbabwe and Finland form a well-defined smoothly decreasing trend in Ni vs. MgO whereas data from the mineralised Kambalda and Scotia regions in Western Australia scatters and numerous samples have anomalously low Ni tenor in a given MgO.

Compared to the above described commonly used techniques, the Co# presented here has some advantages because 1) mafic silicates are often altered, 2) Ni, Co and Cu analyses are commonly available and 3) these assays are far less expensive than mineral analyses and 4) the Co# is easier to interpret (chapter 11.3).

The most serious problem with the Co# and also with the second parameter, the evaluation of the sulphide saturation on the basis of the sulphide content of the sample, lies in the metamorphic mobility of sulphides and metasomatic alteration. All the case study intrusions re-equilibrated, and locally recrystallised (Rörmyrberget), in prograde amphibolite facies metamorphic conditions and subsequently altered in retrograde serpentinisation. The silicate minerals and sulphide fraction show a good equilibrium which, regardless of metamorphic overprint as indicated by relatively high K_{D(Ni-Fe)} sulphide-olivine, reflects magmatic sulphide segregation process. At least in the Svecofennian intrusions, the metasomatic alterations are regarded meaningless and do not prevent the usage of Co# and Ni# in sulphide exploration. In the fertility analysis the fourth parameter evaluates if sulphides are magmatic in origin: the Co# should decrease in parallel with an increasing sulphide content. This is not the case in Rörmyrberget or in Porrasniemi. In both cases the irregularity in the Co# was interpreted as deriving from the unique magmatic history rather than metasomatic origin of sulphides, but at least in Rörmyrberget the alteration process is also possible. Of the tested cases the metasomatic alteration of cumulates is probably most likely to meet in the Cape Smith, Perseverance and

Thompson belt. However, in all of these areas almost all targets show a decrease in the Co# vs. sulphide content which is regarded as a proof that metasomatism has been negligible process regarding sulphides. Evidently metasomatism can hinder the utilisation of the Co# in certain areas like the Abitibi greenstone belt in Canada (Naldrett 2004), and the komatiite belts in Western Australia (Barnes et al. 2004) but the data tested here indicates that these cases are the exceptions rather than the rule.

In Kanada the Mineral Exploration Research Centre of the Laurentian University conducted a study in 1995-1998, which focused on the application of geochemistry to the exploration for komatiite-hosted Ni-sulphide deposits in Canada. The results were published not only in the study report (Burnham et al. 1988) but also in the publications of Lesher at al. (1999 and 2001). The primary study site was the Raglan Horizon, New Quebec, and the methodology developed was tested in the Thompson Nickel Belt, Manitoba (Layton-Matthew et al. 2003). Their data was used in chapter 13.4 and 13.5 to test the fertility analysis developed here. Differently from the population analysis used here, Burnham et al. (1988) aimed to identify case by case whether the sample derived from a mineralised or an unmineralised environment. Using a factor analysis, they developed a 6-element discriminant function based on the Pd, Ir, Th, Cu, Fe and Mn content of samples. High scores were recorded in the mineralised environments. A simplified method was based on the ratios of Th/Nb, La/Sm and Pd/TiO₂. According to Burnham et al. (1988), the Pd/TiO2 of the cumulates indicates whether the magmas from which they formed had reached S-saturation, and the high Th/Nb and La/Sm of the mineralised bodies show that the assimilation of sulphide-bearing sedimentary rocks has played an important role in the production of the magmatic sulphide ores. The Raglan Horizon discriminant function allocated 92 % of the samples to the correct group, mineralised vs. unmineralised. In the test runs of the Thompson

elt, the discriminant function failed and the values for mineralised and non-mineralised bodies overlapped and did not differ significantly.

The fertility analysis of the present study tested with the same data from the Cape Smith and the Thompson belt was much better in discriminating fertile and barren targets in Thompson belt and also in the Cape Smith belt the match was passable. The discrimination indeces based on factor analysis produce effective tools in a training data set but seems to lead in parameters which are geologically difficult to understand and therefore genetic grounds become dim (cf. Häkli 1971, Mäkinen 1987). At least in intrusions but also in extrusions the populaton analysis approach seems to be more stable, i.e. less sensitive to number of samples, than sample-by-sample identification.

Contamination, which according to case studies, seemed to offer an interesting tool for discriminating fertile intrusions, proved out to be very sensitive for sampling. Although the presence of graphite, anomalous Mo and V contents are considered direct evidences of contamination by graphite schist. these indications are often absent even close to the ore and hence far too heterogeneous to be utilised in exploration. Moreover different contamination indicators gave contradictory results in the same samples. Although contamination indicators give valuable information on the genesis of the intrusions they are far too dubious to be used in exploration.

In Australia Barnes et al. (2004) tested potential lithogeochemical indicators to discriminate between unmineralised and mineralised sequences using the CSIRO database of more than 3000 analyses from komatiites all around the world. Tentatively tested tools included the Ni-MgO relationship, PGE in low-S rocks, volcanic facies, MgO-FeO variance, Ni-Cr relationship, Ni-Ti variance and indicators of contamination. The study concluded that there is no universal geochemical indicator for komatiiteassociated nickel sulphide deposits, and that this is because the mineralising systems in komatiites are large open systems involving the prolonged flow-through of large volumes of magma. According to Barnes at al. (2004), the magma, which produced a sulphide ore body, is often decoupled from the sulphide accumulation. They concluded that by far the best and possibly the only reliable geochemical tracer for komatiiteassociated nickel sulphide deposits is the presence of Ni-enriched magmatic sulphides. Nickel must be interpreted in the context of the dominant olivine control on komatiite composition, ideally by reference to the MgO content of the rock, but ratios to Cr and Ti or Al provide an effective substitute (Barnes et al. 2004).

Cameron et al. (1971) came to a fairly similar result. They compared the differences between a total of 61 fertile and barren Ni sulphide targets in Canada on the basis of 1079 samples from which only copper, nickel, cobalt and sulphur were analysed. They concluded that concentrations of sulphur and leachable copper are the best discriminatory elements for the identification of fertile targets. A discrimination factor based on Cu, Ni and Co succeeded in discriminating between a large number of samples from barren, fertile and subeconomic intrusions.

Barnes et al. (2004) rejected sulphur and copper because of their mobility. In such an environment Cu could be omitted from the Co#, i.e. a modified cobalt number, $Co_M\# = 100*Co/(Co+Ni)$, could be used instead. Co and Ni are equally mobile and both are bound in sulphides and also in mafic silicates. Segregation of sulphides causes an increase in the $Co_M\#$ of subsequent cumulates, even if that cumulate is sulphide-free. The $Co_M\#$ should be relatively insensitive to sulphurisation, desulphurisation, and Cu mobility and metasomatism of lithophile elements.

Basically, the identification criteria for the fertile intrusions in this study do not differ notably from those already established in the late 1970s. If Ni exploration has been carried out for about 25 years with this knowledge, is the developed methodology better and is it likely that its application would lead to better results and

new discoveries? There are five significant differences between the fertility analysis and common practices of exploration, using the Nickel Programme as a reference case. First, the discrimination rules of the Ni Programme were inaccurate and were not unambiguously established (Grundström 1982), since the ranking required lots of consideration. Secondly, the Nickel Programme database was a sample database and not a target database like the NIXPLOR database, the descendant of the Nickel Programme database that was used in the testing in chapter 14.3. Therefore it was not possible to run a statistical or population analysis in the Nickel Programme database or it required a lot of manual work. Thirdly, the Fertility Analysis utilises the Co# which can be calculated for all samples with cumulus sulphides whereas Nickel Programme criteria relied on the Ni content of mafic silicates, which cannot be analysed in all samples. Fourthly, the computer capacity to process large databases has increased enormously. In the 1980s Geographical Information Systems (GIS) were non-existent and the processing of the data into maps was largely done by hand (Grundström 1982). Fifthly, nowadays different and large lithogeochemical databases from various areas have become public. e.g. from national Geological Surveys. Selection between areas can now be made on the basis of existing data rather than the exploration organisation having to start to collect the database

The five reasons listed above indicate that utilisation of the fertility analysis even in areas subject to nickel sulphide exploration for decades still has the potential to make some new discoveries.

16.3 Open nature of the magmatic systems and consequences for exploration

Case studies, modelling of the sulphide segregation modelling and mass balance calculations show that studied the intrusions studied have been open and constantly changing magmatic systems. In such an environment different stratigraphic levels mav have accumulated and crystallised from different unrelated magmas and therefore classical fractional crystallisation models do not work (e.g. Hill 2001). Parental magma and crystallisation history analysis has showed that magma composition has changed in a non-linear and unpredictable way (e.g Bruvann, chapter 6.3.1).

However, base metal depletion features were observed in all the fertile intrusions: Bruvann, Laukunkangas and Stormi. In Bruvann depleted cumulates are located stratrigraphically both below and above, whereas in Laukunkangas and Stormi they are found only above the ore in a way that resembles the ideal fractional segregation model. This indicates that although intrusions in details, i.e. in on <10 m scale, are very unpredictable in details, in on the zone zonal and subzonale scale the broad trends can be studied and modelled utilising the techniques of fractional crystallisation and segregation.

16.4 Spatial variation in the nature of Svecofennian mafic – ultramafic intrusions

This fertility analysis gives new information on Svecofennian ultramafic intrusions and their spatial characteristics. The following is based on the parameters of the fertility analysis of the *NIXPLOR* database of Outokumpu including a total of 964 Svecofennian ultramafic-mafic intrusions, 354 of them sampled. Sampling is concentrated on group I intrusions, intrusions of the Arc complex of western Finland (Peltonen 2005), and in them on ultramafic intrusions and on mafic intrusions that contain ultramafic parts. Therefore the following is a summary of characteristics of group I intrusions if not otherwise stated.

Most of the Svecofennian intrusions of groups I-IV, 85 %, are differentiated mafic intrusions About a fourth of them contain olivine cumulates (oC) and about 10 % of them do not contain olivine-bearing cumulates at all; both are based on the amount of normative olivine. The average size of the mafic intrusions is 4.8 km^2 (median 0.27 km²) and Hyvinkää, Joutsenmäki-Tolvanniemi and Forssa are some of the biggest ones (180a).

The ultramafic intrusions are found in the group I only. They are significantly smaller than the mafic intrusions. Their average size is 0.40 km² (median 0.074 km²). Rausenkulma and Etelä-Hitura are some of the biggest. About 70 % of the ultramafic intrusions are found in the narrow belt between the NE corner of Pori (Harjunpää intrusions) and the SE corner of Vammala (Liuksiala intrusion 10 km east from Stormi, 180b).

The compositions of parental magmas of the intrusions vary in terms of Fe/Mg ratio displayed by the maximum forsterite content of olivine and in acidity (SiO₂ n content) shown in the ratio of pyroxenes. The most primitive olivine in the intrusion is mainly Fo₈₀₋₈₅ (181a). Ultramafic intrusions are generally more primitive; the most primitive olivine is on average Fo_{83.3} whereas in the mafic intrusions it is Fo_{80.1}. Most of the intrusions have similar amounts of both but whole range pyroxenes, the from clinopyroxenitic to noritic intrusions exists, the ratio of pyroxenes also varies similarly in the ultramafic intrusions (181b). Group II intrusions, synvolcanic intrusions of the Arc complex of southern Finland, are significantly less primitive and clinopyroxene dominated compared to the group I intrusions.

The most primitive intrusions of group I are concentrated in relatively narrow "sulphide belts" around the Granitoid Complex of Central Finland. The belts are characterised by the high amount of intrusions and high proportion of ultramafic intrusions (Peltonen 2005). In addition, the intrusions are more melanocratic, the parental magma has been more primitive and orthopyroxene dominant normative is the pyroxene (180-182). The belts have a higher metamorphic grade than surroundings and scholle-schlieren migmatites are common, which according to Peltonen (2005) indicates that the belts represent a deeper section of the crust.

A characteristic and profound feature for the Svecofennian intrusions is that very high portion, more than 80 % and in ultramafic almost 90 %, have crystallized from sulphide-saturated magma (183a). This is true also for the group II intrusions. About 30 % of the mafic and 20 % of the ultramafic intrusions are base metal depleted, which has been caused by the removal of sulphides upstream. Base metal depletion is slightly more common in the intrusions dominated by (normative) clinopyroxene. Spatially depleted intrusions are common in the E-SE end of the Pori-Kylmäkoski belt, north side of the Pirkanmaa belt (between Porrasniemi and Koivakkala), in the north end of the Sulkava-Juva belt and on the north side of the intrusions cluster around Hitura (183b).



Figure 180. The nature of Svecofennian intrusions, **a)** size (above) and **b)** intrusion type (below). "All others" contain intrusions with no data to make the analysis.



Figure 181. The nature of Svecofennian intrusions, <u>a)</u> parental magma (above) and <u>b)</u> dominant pyroxene (below). "All others" contain intrusions with no data to make the analysis.



Figure 182. The primitiviness of Svecofennian intrusions, <u>a)</u> the most primitive cumulate (above) and <u>b)</u> primitiviness index (below). "All others" contain intrusions with no data to make the analysis.



Figure 183. The nature of Svecofennian intrusions in terms of \underline{a} sulphide saturation (above) and \underline{b} chalcophile depletion (below). "All others" contain intrusions with no data to make the analysis.

17 SUMMARY AND CONCLUSIONS

In the course of this study a series of indexes and calculation routines for single samples were developed:

- Composition of the sulphide fraction (SF), i.e. sulphides recalculated to 100 %, is calculated using normative sulphide minerals. All Ni is allotted to pentlandite, Cu to chalcopyrite, Co to Co-pentlandite, Zn to sphalerite, Pb to galena, Mo to molybdenite and As to arsenopyrite. Residual S is allotted to pyrrhotite. Normalisation to 100% and back calculation to chemical composition gives e.g. the Ni tenor.
- 2) Composition of the volatile- and sulphidefree composition (*VSF*) is calculated by subtracting the elements bound in sulphides from the whole-rock assay and recalculating that to 100 %. *VSF* provides important information on the nature of ore samples. In addition, it brings both barren and sulphidebearing samples in the same line and their comparison becomes easier.
- 3) B-norm calculates the normative mineral composition of samples in cumulate rocks more reliably than the CIPW norm. The main differences are the presence of phlogopite and individual Mg# of mafic silicates in the B-norm.
- 4) Automated cumulus naming routine gives a proper cumulus name for the rock on the basis of B norm calculated from the VSF chemistry. The thresholds which define whether a mineral is a cumulus phase or not were determined on the basis of microscopical studies.
- Nickel and cobalt numbers, are calculated as follows: Ni#=100*Ni/(Ni+Cu); Co#=100*Co/(Ni+Cu+Co). The indexes describe the composition of the sulphides.
- 6) Calculation routines were packed in software called ApeRock, currently *HSC Geo*, which was used in the sample studies.

Modelling the segregation of sulphides established the usage of Ni# and Co# in

evaluating magma primitiveness and chalcophile depletion:

- 7) Ni# describes the magma primitiveness and the degree of partial melting of the mantle as the parental magma was generated. In komatiites, which represent primitive magmas of a high degree of mantle melting, the Ni# is extremely high, >90. It lowers via picrites (80-90) and tholeiites (50-80) to flood basalts (10-40).
- Within the igneous suite, the most primitive magma has the highest Ni#. The fractionation of olivine decreases the Ni# of the silicate melt.
- 9) Co# describes the segregation of sulphides. The fractionation of olivine causes only a minor increase in Co#. In primary magma the Co# is low. As sulphides segregate from the system, the Co# of the residual increases. This is accompanied by a change in Ni#. The partition coefficient of nickel and copper between the sulphide melt and silicate magma vary. In high-Mg silicate melts, the DNi>DCu and fractionation of sulphides will affect in the same direction as olivine: The Ni# of the residue liquid decreases. In more evolved melts where the Ni#<50 DNi may be smaller than DCu and the segregation of sulphides will affect in the opposite direction than olivine, thus increasing Ni# in the residue liquid. The direction of the net effect if both olivine and sulphides fractionate depends on their mutual ratios.
- 10) Fractionation of pyroxenes has a similar effect on Ni# and Co# as olivine.
- 11) If the amount of sulphides is greater than 0.3 %, Ni# and Co# describes the composition of the sulphides and the effect of non-sulphides is negligible. The effect of non-sulphides can be overcome if sulphide-selective analysis methods (e.g. bromine-methanol leach) are used to determine the base metal content in a sample.
- 12) Based on a literature survey on the

dissolution of sulphur in the mafic magma and simple mass balance calculations, it was found that if the amount of sulphides exceeded 0.3 % in a cumulate rock and provided no secondary mobilization of sulphur has occurred in the rock, it must have crystallised from sulphur-saturated magma.

For the case study targets, three fertile intrusions (Stormi and Laukunkangas in Finland and Bruvann in Norway) three subeconomic (Ekojoki and Rausenkulma in Finland and Rörmyrberget in Sweden) and three barren (Posionlahti and Porrasniemi in Finland and Alter do Chão in Portugal) intrusions were selected. The intrusions are of orogenic type and most of them belong to the group of Svecofennian mafic-ultramafic intrusions, which have been mined for nickel since the 1960s. The grades and tonnages of the fertile intrusions have been relatively modest; in the biggest one, in Hitura, a total of 13.5 Mt ore at 0.60 wt.% Ni and 0.22 wt.% Cu has been treated so far. The most important results of the case studies are:

- 13) Fertile and subeconomic intrusions show direct and indirect evidences of contamination with black schist. Bruvann and Laukunkangas contain partly digested black schist fragments within the intrusion and especially close to the ore. In both, graphite is abundant in the ore, molybdenite is frequently encountered and the VSF chemistry of the ore shows an anomalous high content of V_2O_3 n and MnO n. These features point out the presence of a black schist component in the ore. In Stormi, the chromite is rich in zinc and in the previous studies sulphur isotopes show that part of sulphur is from the crust.
- 14) Barren intrusions differ in two ways from the economic and subeconomic intrusions. Posionlahti and Porrasniemi are depleted in base metals and Alter do Chão is barren of sulphides.
- 15) Fertile and subeconomic intrusions are totally sulphur-saturated; they are not depleted in base metals, and have signs of contamination.

16) Differences in the lithogeochemistry between fertile and subeconomic intrusions are either very small or non-existent. Considering the geology of the targets and comparing the whole data set of the intrusion, the following differences were noted: a) in subeconomic intrusions sulphides are not associated with the most primitive cumulates but more evolved. pvroxenitic cumulates. b) in subeconomic intrusions the sulphide accumulation is located within the intrusion, not in the contact areas and in the primary bottom areas. These features indicate that though subeconomic intrusions are formed from sulphide-saturated melts. the accumulation process has been inadequate.

On the basis of the case studies, a *fertility analysis* was created, which aimed to discriminate between fertile and barren intrusions on the basis of lithogeochemistry:

- 17) The *fertility analysis* consists of seven parameters, which measure whether the ore-forming processes have taken place in the intrusion. They are the quantification of the requirements presented by Naldrett (1989).
- 18) Parameters calculated are using the population analysis technique, where a sample population, i.e. collection of samples from one intrusion, is first filtered in several steps to wash out unrepresentative samples and then the specific key figure is calculated by simple statistical methods. In several key figures, the representative population is divided into sub-populations and the final key figure is the ratio of the key figures of the sub-populations. Ore samples with >0.5%Ni or Cu are excluded in the calculation of every paramer.
- 19) The parameters of the fertility analysis are: i) primitive character of the magma, ii) extent of sulphide saturation. iii) Ni-rich. chalcophile undepleted magma, iv) sulphides are magmatic and equilibrated with a large amount of magma, v) coeval primitiveness, vi) sulphide accumulation and vii) fractionation or mobilisation of sulphides.

- 20) Parameters have been put in the order of tightening requirements, and the ranking method is screening. Targets passing the step in question continue to the next step, while rejected targets get the number of the last step they have passed as the *overall discrimination value* (*OD*). The *OD* value ranges from 0.000 to 7.499. The higher the value, the more prospective the target.
- 21) Several potential tools to identify the important contamination process were tested. Though the presence of a black schist component is clearly indicated in ore samples, the features are far too localised, heterogeneous and faint to be used in the screening of potential intrusions. Isotope analyses may be more sensitive, but the high cost of the analyses and difficulties in interpreting the result and identifying the contamination leading to ore formation weakens these methods.
- 22) Compared to previous studies aiming to develop methodology for discriminating Ni-Cu- (PGE) mineralised intrusions and extrusions, this study has resulted in a unambiguous, well-defined and documented system for classifying exploration targets. The number of samples from each target required is only about 25, which are subject to ordinary whole-rock analysis. A decision tree has been described in detail, so that it is possible to create an automated system for calculating the OD value for each target.
- 23) The main differences compared to most of the other earlier studies are that the degree of sulphide saturation is measured directly from the abundance of sulphides and the identification of favourable contamination, which has been regarded as a very important exploration tool, is practically abandoned here.
- 24) Instead of olivine composition the Co# is used to identify favourable chalcophile depletion in the third parameter. The Co# is also utilised in the fourth, fifth and seventh parameters.

- 25) The Co# has several advantages compared to other commonly used sulphide segregation indications, e.g. the Ni content of olivine: i) mafic silicates are often altered, ii) Ni, Co and Cu analyses are commonly available, and iii) are far more inexpensive than mineral analyses, iv) Co# is easier to interpret and v) it measures directly the composition of the ore forming phase: sulphides.
- 26) In fertile intrusions, the Co# decreases towards the ore. In Stormi and Laukunkangas this is a clear and well-defined feature, but in Bruvann more obscured.

The methodology developed, the *fertility analysis,* was tested extensively using large data sets from Svecofennian mafic-ultramafic intrusions, the Thompson belt and the Cape Smith belt. Furthermore, the *OD* value of numerous world-class Ni-Cu- (PGE) deposits was calculated. The results of the tests are:

- 27) The fertility analysis is capable of discriminating between barren and fertile targets in all the test areas.
- 28) The OD value of a total of 353 Svecofennian ultramafic-mafic was calculated based on 7517 samples. The OD value of exploited Ni-Cu ores was between 4 and 7 and the average was 5.88. The average OD of the subeconomic intrusions was 5.01 and that of barren intrusions 2.95.
- 29) The test data from the Thompson Ni belt included 1207 analyses from 31 targets. The average OD value of the fertile and subeconomic targets is the same, 4.9, whereas in barren targets it is significantly lower, 2.5.
- 30) The Cape Smith test data included a total of 287 samples from mineralised and unmineralised komatiitic environments. The degree of sulphide saturation discriminated targets in two groups so that komatiite units from mineralised environment received an average OD value of 4.5 whereas those from an unmineralised environment received only 1.3.
- 31) Test with samples from the world class Ni-

Cu (PGE) deposits: Pechenga and Noril'sk-Talnakh in Russia, Sudbury and Voisey's Bay in Canada, and Perseverance in Australia, showed that the primitiveness criterion and MgO_n filter used are not relevant in largely mafic intrusions like Voisey's Bay, Noril'sk and Sudbury. In the two latter, the sulphide saturation was restricted close to the ore and due to the essential role of the Co# *fertility analysis* fails in these targets. The *fertility analysis* works properly only in areas where sulphide saturation is an ordinary feature in targets of Ni exploration.

The relationship between the Co#-Ni# and PGE was studied using large data sets from Duluth and Keivitsa. The results are:

- 32) PGE correlates negatively with Co# and high PGE contents are frequently found in samples poor in Co#. The correlation of PGE with Co# is significantly better than the correlation with S, Cu or Ni.
- 33) In all the PGE deposits (Sudbury, Suhanko, Duluth, Keivitsa) the Ni# is low. The association of low Co# (<2) with low Ni# (<50) cannot be due to the fractionation of olivine from the magma with a higher Ni#, but it is regarded either as an indication of PGE rich melt that has experienced sulphide segregation with high R, or that sulphide melt has fractionated.
- 34) On the basis of observations, a decision tree was established to screen PGE potential intrusions on the basis of the Ni# and Co#: The requirements are: i) Ni#<50, ii) a positive relationship between the Ni# and Co# and iii) Co#<2. The lower the minimum Co# of the target, the more promising it is for PGE.

The fertility analysis and the PGE decision tree give promising results and the following recommendations are given on its usage in the exploration of Ni-Cu-PGE:

35) Co# plays essential role in the fertility analysis. The use of selective leaching methods like bromine-methanol leach for the analysis of Ni, Cu and Co improves significantly the accuracy of Co# and the quality of the fertility analysis. This should be considered when selecting analysis methods for the exploration project.

- 36) The fertility analysis and the use of Co# have been developed for the geological environments where sulphide saturation is common feature in Ni exploration targets. New areas should be evaluated from this perspective before the application of the fertility analysis.
- 37) An essential point in the fertility analysis is that sulphides are primary and the target has not suffered from a significant sulphurisation or desulphurisation process. This is evaluated by the fourth parameter, "sulphides are magmatic and equilibrated with a large amount of magma" but all available information should be used to verify this matter.
- 38) The methodology should be used in combination with other techniques. In particular, various geophysical methods are powerful in localising and delineating potential drilling targets.
- 39) The results of the fertility analysis should be compared continuously and in all exploration stages to the ore model established from the area and the targets. The models covering the geological and geophysical development of the area and target should indicate the most potential geological environments, targets and sites within the targets.
- 40) The fertility analysis is based on the key processes of the Ni sulphide ore formation, and it gives a measurable value for each of them. It is relatively easy to computerise and to be run with large databases. The best usage of the fertility analysis is to collect a summary of each of the exploration target and to put them in tentative order of ore potential to be further evaluated with geological knowledge and other available information.

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248 Geological Survey of Finland Bulletin 402 Pertti Lamberg

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256 Geological Survey of Finland Bulletin 402 Pertti Lamberg

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20 TERMS AND NOMENCLATURE

- \$: Used for a sulphide in cumulus names, e.g. o\$C, an olivine-sulphide cumulate. In this study cumulus names are generated from the volatile- and sulphide-free composition to bring out the nature of the host rock of the sulphides. Therefore samples, which contain cumulus sulphides are here referred to without the \$ symbol.
- %: Percentage, in this study the composition of a rock, chemical or mineral, is given in weight percentages. The symbol wt.% is used to stress that the number is based on an original analysis result, e.g. Ni wt.%.
- _n: Volatile- and sulphide-free content in weight percentages.
- **a**: Used for clinopyroxene in cumulate names, comes from augite. E.g. aoC,clinopyroxene-orthopyroxene cumulate.
- Adcumulate: A cumulate rock, where cumulus minerals comprise more than 93% of the rock.
- Amp: Amphibole.
- Apy: Arsenopyrite, FeAsS.
- **b**: Used for orthopyroxene in cumulate names. The b comes from bronzite, e.g. baC, orthopyroxeneclinopyroxene cumulate
- **Barren cumulate**: In this study a barren cumulate is a cumulate rock, which contains less than 0.5% Ni and Cu.
- **Barren cumulate with cumulus sulphides**: A cumulus rock, which contains less than 0.5% Ni and Cu but more than 0.3 % normative sulphides.
- **Barren intrusion**: Here intrusions are divided into fertile, subeconomic and barren. A barren intrusion is, according to current knowledge, not very likely to host any significant mineralisation.
- **Block**: A separate part of an intrusion, in most cases it was separated by tectonic displacement.
- **BM**: A bromine-methanol dissolution. Selective dissolution method of sulphides (Penttinen et al. 1977).
- **B-Normative:** B-normative mineral composition of the rock, B comes from basalt. Expresses the inferred primary igneous mineral composition of the rock crystallised from basaltic melt. Differs from CIPW normative mineral composition by having phlogopite

in the norm, i.e. K is allocated in phlogopite instead of K-feldspar. Also, the Mg# of mafic silicates is individual for each species. In this study the Bnormative mineral composition is calculated from the volatile- and sulphide-free composition, VSF, and B norm expresses the non-sulphidic portion of the rock. This is to bring ore samples, sulphide bearing and barren cumulates into line.

Box and whisker diagram: A diagram to illustrate the statistical variation (see figure on right). It consists of a small box showing the median, larger box showing the 25th percentile (LBV) and 75th percentile (UBV) and whiskers indicating non-outlier minimum and maximum. Circles indicate the outliers and stars the extremes. A data point is deemed to be an outlier if the following conditions hold: data point value > UBV + o.c.*(UBV - LBV), or data point value < LBV - o.c.*(UBV -



LBV). A data point is deemed to be an extreme value if the following conditions hold: data point value > UBV + 2*o.c.*(UBV - LBV), or data point value < LBV - 2*o.c.*(UBV - LBV). The outlier coefficient o.c. is equal to 1.5. The number in parenthesis below each box and whisker gives the number of cases in the class.

- **BN**: Symbol used for B-normative, e.g. Ol_BN%, B-normative olivine content. See B-Normative.
- C: Used for cumulates, e.g. oC: olivine cumulate.

Ccp: Chalcopyrite, CuFeS_{2.}

- **Chalcophile element**: Metals at the centre and righthand side of the periodic table (Ag, As, Bi, Cd, Cu, Ga, Hg, In, Pb, Po, S, Sb, Se, Te, Tl, Zn) having an affinity to sulphides, most commonly occurring in sulphide minerals.
- Chr: Chromite.
- **CIPW:** Normative mineral composition calculated according to Cross, Iddings, Pirsson and Washington, CIPW. (Cross et al. 1903).

- **Co#, Cobalt number**: 100*Co/(Ni+Cu+Co) of the sulphide fraction (wt.% / wt.%). Can be calculated for melt and rock, but then it should be marked (Co#^{Rock}, Co#^{Silicate melt}). Can be used as an indicator of the base metal depletion.
- **Compatible (element)**: Element, which is compatible in the structures of minerals crystallising and fractionating from the silicate liquid. The Nernst partition coefficients of these minerals are greater than one.
- **Complex**: A major layered intrusive complex; can contain several intrusions (e.g. Bushveld complex, Stormi is a complex consisting of several ultramafic intrusions).
- Contamination: Mixing of magma with wall-rock.
- **Cpn**: Cobalt pentlandite, $(Co, Fe, Ni)_9S_8$, normative cobalt pentlandite used in this study is Co_9S_8 in composition.

Cpx: Clinopyroxene, Ca(Mg,Fe)Si₂O₆.

- **Cumulate:** A magmatic rock whose texture and composition shows that it has been formed by the magmatic accumulation process, where crystallising minerals have been concentrated mainly due to gravity to form more than 50% of the rock. A cumulate consists of cumulus and intercumulus minerals. Interstitial liquid has crystallised to form intercumulus minerals. In this study a rock is identified as a cumulate, if the sum of the normative cumulus minerals exceeds 50%. A mineral is identified as a cumulus mineral, when the amount exceeds the mineral-specific threshold value given in Table 11.
- **Cumulus mineral**: (in this study, normative definition) Mineral in a cumulate rock, whose amount exceeds the threshold set for cumulus phases (**Table 11**).
- **Cumulus name**: Name of a cumulate, where cumulus minerals are listed first in the order of decreasing abundancy, then letter C for cumulate, which is followed by intercumulus minerals in the order of decreasing abundancy. Intercumulus minerals are often left out. E.g. obCa, olivine-orthopyroxene cumulate with clinopyroxene as intercumulus mineral.
- **Cumulus sulphides**: A cumulate, which was crystallised in sulphide saturation and therefore contained sulphides as a cumulus phase. In this study it is identified from the normative sulphide content. If the normative sulphide content is higher than 0.3%, then sample contains cumulus sulphides and sulphides is listed with cumulus minerals, e.g. osC, olivine-sulphide cumulate.
- **CV**: Coefficient of variation, a statistical measure of the deviation of a variable from its mean. It is calculated as follows: CV = 100*(standard deviation)/(mean value).

- **Cyclic unit** (Irvine 1982): a rhythmic unit in which the cumulus-mineral sequence can be identified as the fractional crystallisation order of the magma.
- **Cyclic unit**: Unit within other similar units, which is composed of rocks produced by fractional crystallisation of magma. One cyclic unit represents a fractionation series, which is cut off by the beginning of the net cyclic unit. Often interpreted to be formed after new influx of magma into the magma chamber. See rhythmic unit.
- **Depleted, depletion**: Silicate liquid is said to be depleted with respect to an element (for example nickel-depleted), if the concentration of the element in question is below the value expected on the basis of fractional crystallisation of silicates and oxides only (no sulphides). According to the Co# of the sulphide fraction, the magma from which sulphides have segregated is classified as non-depleted when the Co#<10; slightly depleted when the Co#=10-20; depleted when the Co#>30.
- **Differentiation index**: Index calculated form the CIPW normative composition describing the degree of magmatic differentiation.
- **Differentiation**: Magma differentiates in fractional crystallisation, i.e. the composition of magma changes due to the segregation of crystallising phases. In basic magmas, fractional crystallisation of olivine drives the magma to a lower MgO.
- **Distribution coefficient**: Synonym to partition coefficient, i.e. ratio of element content in *phase a* to that of in *phase b*. Normally *phase a* is a mineral and *phase b* is a silicate liquid and the contents of elements in phases are given in wt.% or ppm.
- **Evolved**: Magma, which has formed after significant fractional crystallisation of the parental magma.
- **F**: Fraction of original liquid remaining in the fractional crystallisation and segregation process.
- **Fertile cumulate**: In this study a cumulate, which contains Ni >0.5 wt.% or Cu >0.5 wt.%.
- **Fertile intrusion**: In this study an intrusion, which has been mined for Ni-Cu sulphide ore.
- Fo: Forsterite content of olivine in mole percentages, the mole percentage of forsterite end member, Mg_2SiO_4 in olivine.

Ga: Galena, PbS.

- **Gph**: Graphite, C.
- Group: Prominent combination of several similar units.
- **Incompatible (element)**: (In this study) Element, which is not compatible in the structures of minerals, which are currently crystallising and fractionating from the silicate liquid. The Nernst partition coefficients of these minerals are much less than one.

- **Intercumulus mineral**: (in this study, normative definition) Mineral in a cumulate rock, in an amount that is less than the specific threshold set for it.
- **Intrusion**: Igneous rock unit, which formed as the magma intruded into the crust, and crystallised as it cooled down.
- **Intrusion**: Igneous rocks produced in subsurface condition by a single magmatic system.
- **K**_D: Exchange partition coefficient, describes the partition of two elements between two phases, e.g. exchange partition coefficient of Ni and Fe between sulphide melt and olivine.

$$K_{D_{(Ni-Fe)}}^{\textit{sulfide/olivine}} = \left(\frac{NiS}{FeS}\right)_{sulfide} / \left(\frac{NiO}{FeO}\right)_{olivine}$$

- **m**: Used for magnetite in the cumulus names, e.g. pmC, plagioclase-magnetite cumulate.
- **Magnesium number, Mg#**: 100*Mg/(Mg+Fe²⁺), as cation percentages.
- Mg#: Magnesium number, 100*Mg/(Mg+Fe²⁺), as cation percentages.

Mgt: Magnetite, Fe₃O₄.

- **Member**: An outstanding single unit in the subdivision of an intrusion.
- MgO_n%: Volatile- and sulphide-free magnesium oxide content of the rock in weight percentages.
- **Mesocumulate**: A cumulate rock, where cumulus minerals comprise 75-93 % of rock.
- **Modal composition, mode**: True microscopically observed mineral composition of the sample. Due to alteration may be totally different than primary magmatic mineral composition or normative composition. Compare to normative mineral composition.
- **moln**: Molecular normative composition of the rock. Used in the basalt tetrahedron projections, e.g. Ol moln = molecular normative amount of olivine.
- Mb: Molybdenite, MoS₂.
- *Mss*, monosulphide solid solution: Ni-Cu-Fe sulphide melt starts to crystallise above 1000°C with the appearance of Fe-rich monosulphide solid solution $Fe_{(1-x)}S Ni_{(1-x)}S$.
- N: In sulphide segregation with zone refining N is the ratio of the amount of magma passing through the system and reacting with the sulphide to the amount of sulphide in the system.
- Ni: Nickel
- Nickel content of sulphide fraction, nickel tenor: Nickel content of fraction consisting of sulphides recalculated to 100%. The expression "*tenor*" is favoured. See sulphide fraction, nickel tenor.
- Nickel number, Ni#: 100*Ni/(Ni+Cu) of the sulphide fraction. Can be calculated also for silicate melt and rock, but then it should be mentioned (Ni#^{Rock}, Ni^{Silicate melt}).

- **Nickel tenor**: Nickel content of fraction consisting of sulphides recalculated to 100%. See sulphide fraction, nickel content of sulphide fraction.
- **Normal differentiation**: Evolution path in mineralogy, mineral chemistry or whole-rock chemistry, which is expected when the magma in question would experience normal fractional crystallisation. This can be seen for example in the decreasing forsterite content of olivine, change in cumulates from olivine cumulate via olivine-clinopyroxene cumulate to clinopyroxene cumulate.
- Normative composition: Calculated mineral composition of the rock, e.g. CIPW normative mineral composition, B-normative mineral composition. B-normative mineral composition is in weight percentages. If not otherwise stated, in this study normative mineral content refers to B norm. Compare to modal composition.
- **Normative content**: The amount of normative mineral in the sample, e.g. normative olivine content is 10 %. See modal composition.
- **OD**: Overall discrimination index, varies between 0 and 7.499, the higher the value, the more prospective the intrusion or extrusion for nickel-copper sulphide ore.
- **o**: used for olivine in cumulate names, e.g. obC, olivine-orthopyroxene cumulate.
- Ol: Olivine, (Mg,Fe)₂SiO₄.
- Opx: Orthopyroxene, (Mg,Fe)SiO₃.
- **Ore sample**: (in this study) Sample, which derives from the ore polygon created in the mining plan. In this study also a sample containing more than 0.5% nickel.
- **Orthocumulate**: A cumulate rock, where the cumulus minerals comprise 50-75% of rock.
- **Parental magma**: A magma from which a certain intrusion has crystallised.
- **Partition coefficient**: The Nernst partition coefficient is the ratio of an element in *phase a* to that in *phase b*. Normally *phase a* is mineral and *phase b* is silicate liquid and contents of elements in phases are given in wt.% or ppm.
- PGE: Platinum group elements
- Phl: Phlogopite, K(Mg,Fe)₃Si₃AlO₁₀(F,OH)₂.
- **Pl**: Plagioclase, CaAl₂Si₂O₈-NaAlSi₃O₈.
- **Pn**: Pentlandite, (Ni,Fe)₈S₉, normative pentlandite used in this study is (Ni_{4.76}Fe_{4.24}S₈) in composition.
- **Po**: Pyrrhotite, Fe_{1-x}S. Normative pyrrhotite used in this study is FeS in composition.
- **Primary magma**: A magma whose chemical composition has not changed since formation by partial melting in the mantle. Compare to parental magma

- **Primitive**: Magma, which has not experienced significant fractional crystallisation after the parental magma. Characterised by high Mg# and Ni content.
- Px: Pyroxene.
- Py: Pyrite, Fe₂S.
- **R factor**: The mass ratio of sulphide melt to silicate melt in batch segregation of sulphides from the silicate melt.
- REE: Rare earth elements.
- **Restite**: The remaining refractory residual part, which does not melt and mix with magma when a crustal material, e.g. sedimentary rock, interacts with magma.
- **Reversal**: An event where the composition of magma reverts to a more primitive one. In most cases it is interpreted as an influx of primitive magma.
- **Reverse differentiation**: Evolution path in mineralogy, mineral chemistry or whole-rock chemistry, which is reversal to normal fractional crystallisation. Quite often reverse differentiation is noted from the increasing Mg# of the mafic silicates. In quite a lot of intrusions in this study reversal marks the exact border between a marginal series and layered series.
- **Rhythmic unit**: Stratigraphic unit of an intrusion. A succession of layer types that is repeated stratigraphically in a regular way (Irvine 1982).
- **SCSS**: Sulphur content of the silicate melt in sulphide saturation.
- **Series**: Stratigraphic unit in an intrusion. Major stratigraphic successions of cumulates that can be a part of intrusion or block.
- **Sp**: Sphalerite, (Zn,Fe)S. Normative sphalerite used here is ZnS in composition.
- Srp: Serpentine, Mg₃Si₂O₅(OH)₄.
- **SS**: Total amount of sulphide segregated from the system, initial melt = 100. In batch segregation of sulphides where R = silicate melt/sulphide melt, SS=100/(R+1).
- **SCS**: 100*sulphide/(sulphide+olivine) in the segregated phases. In the batch and zone refining process SCS is 100% whereas in the fractional segregation of sulphides + olivine in cotectic proportions SCS is typically around 1.
- **Subeconomic intrusion:** Here intrusions are divided in fertile, subeconomic and barren. A subeconomic

intrusion hosts a mineralisation, which has not been utilised due to low grade and tonnages.

- **Subzone**: Stratigraphic igenous unit in an intrusion. Second-rank stratigraphic subdivision of series, part of a zone. Mostly non-mappable. Identified by chemistry and mineralogy.
- Sulph: Sulphide minerals.
- Sulphide fraction, SF: In solid rock, sulphides recalculated to 100%, weight percentages. In most of the mafic and ultramafic rocks this is pyrrhotite + chalcopyrite + pentlandite. In magma, molten or partly solidified sulphides, recalculated to 100%, weight percentages. See also tenor.
- **Tenor**: E.g. Ni tenor, PGE tenor; is the metal content in the sulphide fraction (see sulphide fraction).
- **Unit**: Stratigraphic igneous unit in an intrusion. Compositionally distinctive features that can be singled out and named or numbered for specific reference. They are not necessarily part of anything except the intrusion.
- **Volatile-free**: VF, Volatile-free chemical composition of the rock in weight percentages.
- **Volatile-** and sulphide-free: VSF, volatile- and sulphide-free chemical composition of the rock in weight percentages. In figures and tables the postfix n% is used to refer to VSF composition, e.g. $MgO_n\%$ is volatile- and sulphide-free MgO content in weight percentages.
- **VF**: Volatile-free chemical composition of the rock in weight percentages.
- vs.: versus (Latin), against.
- *VSF*: Volatile- and sulphide-free chemical composition of the rock in weight percentages.
- **Whole-rock**: Used for composition, whole-rock composition, whole-rock analysis. Is the total composition of the rock or total analysis of the rock. Used to differentiate analyses and composition thereafter where only part of the minerals are subject to assay, e.g. nitric acid dissolution + ICP.
- wt.%: Weight percentage. In this study most of the compositions are in weight percentages, even if only the % symbol is used without wt. prefix.
- **XRF**: X-ray fluorescence analysis, analysis method to determine the whole-rock composition of a sample.
- **Zone**: First-rank stratigraphic subdivision of series, mappable part of a series.

21 INDEX

Alter do Chão, 151 Geological model, 154 Subdivision, 152 ApeKraph, 39 ApeModel, 26, 31 Batch segregation, 20, 21, 28, 30, 164, 166, 167, 169, 170, 171, 261 Birchtree, 207, 208 Black schists, 18 B-norm, 43, 45, 47 Bowden Lake, 207 Bromine-methanol leaching, 37 Bruvann, 51, 52, 54, 56 Contamination, 71 Genetic considerations, 66 Geological model, 80 Nickel-copper ore, 61 Parental magmas, 69 Sulphide segregation model, 166 Bucko Lake, 207 Chalcophile element depletion, 20, 21, 22, 23, 75, 79, 80, 81, 95 Chromite, 10, 50, 51, 58, 61, 110, 121, 124, 145 Stormi, 108 Zinc content, 13, 18, 115, 175 CIPW, 43 Co# Co#vs. Co content, 159 *Co\#vs. sulphide content, 157* definition, 25 In Ni-Cu deposits, 34 In silicate melts, 25 Initial Co#, 164 Ouantitative model, 165 Resetting of Co# and Ni#, 161 Co# vs. Ni# graph Alter do Chão, 157 Bruvann. 64 Bruvann model, 167 Cape Smith, 227 Duluth, 221 Ekojoki, 124 Ekojoki model, 169

Hitura. 206 Initial compositions, 165 Kevitsa, 222 Kotalahti. 206 Kvlmäkoski, 206 Laukunkangas, 94 Laukunkangas model, 167 Pechenga, 212 Perseverance. 214 PGE exploration, 229 Porrasniemi, 148 Porrasniemi model, 172 Posionlahti. 143 Posionlahti model. 172 Rausenkulma, 130 Rausenkulma model, 169 Rörmvrberget, 139 Rörmyrberget model, 170 Stormi, 112 Stormi model, 170 Sudbury, Worthington sill, 219 Svecofennian intrusions, 227 Talnakh, 217 Thompson Ni belt, 227 Trends, 165 Crustal contamination, 11, 17, 81, 225 Cu/Zr ratio, 13, 22 Cumulus name Normative, 46, 47 D_{Co} Sulphide-silicate, 28 D_{Cu} Sulphide-silicate, 28 Depleted, 33 D_{Ni} Sulphide-silicate, 28 Duluth, 17, 18, 210, 211, 215, 216, 220, 221, 222, 223, 224, 225, 226, 227, 242, 243 Ekojoki, 115 Geological model, 126 Mineralisation, 122 Subdivision, 117 Sulphide segregation model, 168 Europium

Use in exploration, 22 Evolved, 33 Extremely depleted, 33 Fertility analysis, 173, 174 Auxiliary parameters, 187 Cape Smith belt, 209 Decision tree, 192, 193 Duluth, 215 Effect of number of samples, 197 Jinchuan, 211 Parameter 1, 174 Parameter 2, 175 Parameter 3, 179 Parameter 4, 180 Parameter 5, 182 Parameter 6, 185 Parameter 7, 186 Parameters, 176, 177 Pechenga, 210 Perseverance, 213 Råna intrusion, 201 Ranking, 189, 190 Svecofennian intrusions, 203, 204 Talnakh, 215, 217, 218 Thompson Ni belt, 207 World-class deposits, 210 Fractional segregation, 20, 21, 29, 30, 31, 32, 35, 78, 164, 166, 167, 168, 169, 170, 171, 172, 261 GeoNickel, 10, 173 Graphite, 17, 18, 37, 69, 72, 73, 87, 90, 95 HSC Geo, 39, 239 Hyvelä, 34, 204 Jinchuan, 24, 60, 67, 161, 210, 211, 213 K_D, 24, 161, 162, 163, 231, 260 Kotalahti, 17, 33, 34, 49, 50, 82, 149, 203, 204, 205, 206 Kylmäkoski, 17, 33, 34, 98, 203, 204, 206, 230, 234 Laukunkangas, 82 Chemistry, 87 Genetic considerations, 92 Geological model, 92 Geology, 83 Mineralogy, 87 Nickel-copper ore, 87 Subdivision, 83 Sulphide segregation model, 166 Makola, 33, 34 Moderate primitive, 33

Mss, 21, 23, 27, 30, 33, 35, 65, 82, 113, 115, 125, 126, 186, 260 Nernst partition coefficient, 19 Nernst partition coefficients, 21, 259 Ni# definition, 25 In Ni-Cu deposits, 34 In silicate melts, 25 Nickel Programme, 10, 38, 82, 229 Niinimäki, 203, 204 NIXPLOR, 10, 233 Noril'sk, 16, 17, 18, 23, 33, 210, 215, 216, 219, 226, 227 OD, overall discrimination value, 173, 179, 180, 182, 185, 187, 189, 190, 191, 192, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 208, 209, 210, 211, 213, 214, 215, 216, 217, 218, 219, 228, 229, 241 Olivine Calculated composition, 45 Ni content of normative olivine, 45 Orbicular peridotite, 118, 121 Outokumpu-type ores, 25 Pd/Cu ratio, 13, 22 Pechenga, 17, 18, 33, 34, 210, 211, 212, 243 Perseverance, 161, 210, 213, 214 PGE, 65 PGE exploration, 2, 16, 220, 221, 222, 228 Pipe 1, 208 Porrasniemi, 145 Geological map, 146 Geological model, 150 Radiometric dating, 149 Subdivision, 145 Sulphide segregation model, 172 Posionlahti, 141 Genetic considerations, 145 Sulphide segregation model, 168 Primitive, 33 R factor, 20, 23, 25, 28, 29, 30, 78, 166, 168, 172, 226, 261 Raglan, 18, 209 Råna, 52, 54 Rausenkulma, 126 Geological model, 132 Subdivision, 128 Sulphide segregation model, 168 Rayleigh equation, 20 REE, 18, 120 Rörmyrberget, 133

264 Geological Survey of Finland Bulletin 402 Pertti Lamberg

Genetic considerations. 139 Sulphide segregation model, 168 S/Se ratio, 18 SCS, 30 SCSS, 16 SF, 39 Soab Lake, 208 Stormi, 98 Geological model, 114 Metapicrite, 103 Ore. 111 Subdivision, 100 Sulphide segregation model, 168 Upper serpentinite, 100 Subdivision, 47, 52, 100, 145 Alter do Chão, 152 Bruvann, 53 Ekojoki, 117 Porrasniemi, 146 Rausenkulma, 128 Stormi, 100, 105 Sudbury, 16, 23, 33, 34, 210, 211, 218, 219, 226, 227, 242

Sulphide saturation, 13, 16, 19, 81, 176, 190, 201, 211, 215, 216, 218, 219, 238 Sulphide segregation, 19 Sulphide-saturated magma, 19, 40, 126, 215, 234 Svecofennian mafic – ultramafic intrusions, 9 Svecofennian mafic-ultramafic intrusions, 2, 8, 10, 16, 23, 50, 58, 115, 141, 149, 203, 204, 205, 206, 210, 227, 228, 230, 231, 233, 234, 235, 236, 237, 238, 243 Talnakh, 23, 34, 210, 211, 215, 216, 217, 218, 219, 226 Telkkälä, 230 Tenor, 39 Thallium Use in exploration, 22 Thompson Ni belt, 207 Undepleted, 33 VF, 42 VFS, 42 Voisey's Bay, 15, 17, 23, 210, 217, 218, 219 Zone refining, 20, 260, 261

22 APPENDIX: DATA CD

Enclosed CD includes all the analytical data of the case study targets as given in the ReadMe.txt -file.

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