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by
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GEOCHEMICAL CHARACTERISTICS OF SVECOKARELIDIC MAFIC-ULTRAMAFIC INTRUSIONS ASSOCIATED WITH NI-CU OCCURRENCES IN FINLAND

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The present paper deals with the magma-petrological evolution of 35 mafic and ultramafic intrusions and factors pertinent to the formation of nickel-copper sulphides in them. The total number of samples was 3055. The intrusions were emplaced during the Svecokarelidic orogeny and most of them occur in the belts of Raahe-Ladoga and Ahlainen-Kylmäkoski.

The emphasis of the study is on the statistical handling of geochemical data, which are classified with the aid of clustering and discrimination analysis. The results obtained are then examined against the background of the petrology of the rocks and the structures of the intrusions. The interpretation of the data is largely based on factor analysis. The differentiation in the lithological groups rich in sulphides and poor in sulphides is studied by applying the sliding average technique. The significance of the results is tested with a regression model.

In the first part of the study attempts are made to find factor types that describe certain magmatic events. The factors of each intrusion referring to differentiation are classified into 13 groups, whose geological background is established with the aid of petrographical observations. The geochemical data of the intrusions are then described and interpreted using factor variables and factor scores. On the basis of the factor types and petrology the intrusions are divided into three groups:

1) Kotalahti type intrusions, in which differentiation proceeded from peridotites to norites or other gabbroic rocks. Clinopyroxene, which crystallized as the intercumulus mineral of olivine and orthopyroxene at the beginning of crystallization, was later replaced by plagioclase. Mafic rocks abound relative to ultramafics, which are characterized by a high abundance of orthopyroxene.

2) Vammala type intrusions, in which differentiation proceeded from peridotites to pyroxenites rich in clinopyroxene, and further to gabbroic rocks. Clinopyroxene is the only intercumulus mineral of olivine and orthopyroxene. The proportion of mafic rocks is low relative to that of ultramafics.

3) Gabbro intrusions, in which differentiation proceeded from gabbroic rocks to diorites and quartz diorites. The proportion of ultramafics is very low.

The differences between the rock series of the Kotalahti and Vammala types are ascribed to differences in the magmas generated from different mantle-matter under different P-T conditions. The starting material of the Kotalahti-type magmas was richer in incompatible elements than that of the Vammala-type magmas. The composition of the starting material is also reflected in the gabbro intrusions, because those rich in aluminium are located close to the Kotalahti-type intrusions. The Kotalahti-type magmas were generated at higher pressure (>20 kbar) than the Vammala-type magmas. The high abundances of incompatible elements in the Kotalahti-type rock series may also result from the lower degree of partial melting. The crystallization conditions of the intrusion types also differed, for the Kotalahti-type intrusions crystallized under plutonic conditions, and the Vammala-type intrusions close to the ground surface.

The abundance of nickel-copper sulphides in a rock depends largely on the degree of fractionation. The rocks richest in sulphides are primitive in composition, whereas the rocks poorest in sulphides represent late-differentiates. The rocks rich in sulphides are often also rich in SiO_2 and poor in TiO_2, Al_2O_3, FeO(tot), SrO, P_2O_5 and ZrO_2. However, some rocks rich in sulphides are poor in SiO_2 but rich in FeO. The difference in composition between the barren and ore-potential rocks is attributed to the fractionation of olivine and sulphides. In places, high Cr_2O_3 contents are associated with the ore potential, although the results are ambiguous. The formation of the nickel-copper sulphides is also related to the primary composition of the magma. In the Kotalahti-type intrusions, sulphides occur in both peridotites and norites, whereas in the Vammala-type intrusions the sulphides prefer the peridotites. Pyroxenites contain sulphides less often. The nickel content of olivine is higher in the Kotalahti-type rocks than in the Vammala-type rocks. The differences are ascribed to the properties of the magma types, because experimental studies have shown that the high abundance of normative hypersthene reduces the solubility of the sulphide phase in silicate melt, and normative plagioclase promotes the binding of nickel to olivine.

Key words: igneous rocks, mafic composition, ultramafics, intrusions, geochemistry, nickel ores, copper ores, genesis, statistical analysis, Proterozoic, Finland.

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1. PREFACE

In 1960 Outokumpu Oy launched a nickel programme aiming at an objective assessment of the nickel contents of mafic and ultramafic rocks in Finland. Since then, intrusions of many different types have been sampled at varying density. The findings of the programme have been used to localize targets favourable for the occurrence of Ni-Cu ore deposits and to clarify the factors that contributed to the genesis and oreforming processes of the individual intrusions.

To date about 23 000 samples have been taken for the nickel programme. The voluminous material thus accumulated has served as a basis for a wide variety of studies on diverse subjects and scales. The first findings covering the whole nickel programme were published by Häkli (1970, 1971). Several other studies have also been undertaken on the individual intrusions sampled for the nickel programme, of which the majority were published or referred to in the compilation edited by Papunen and Gorbunov (1985).

The present work is based entirely on the analytical data of the nickel programme. The data represent a cross-section of the whole material gathered for the nickel programme, and the 35 best sampled mafic and ultramafic intrusions of the programme constitute the subject of the present study.

2. INTRODUCTION

The Finnish Baltic Shield consists of two major geotectonic units: the Archaean basement complex, which developed 2 600—3 100 Ma ago, and the Svecokarelidic plutonic and geosynclinal complex, which developed 2 200—1 800 Ma ago (Fig. 1). The Svecokarelidic supracrustal rocks can be further subdivided into the Karelidic formations of the mio-epicontinental facies and the Svecofennidic formations of the eugeosynclinal facies. The postsvecokarelidic rapakivi granites (1 700—1 540 Ma) and Jotnian formations (1 400—1 270 Ma) are the youngest units (Simonen 1980).

Magmatic activity was intense in the area that is now Finland during the Svecokarelidic orogeny, since about 80% of the region covered by the Svecofennides and 40 % of that covered by the Karelides are plutonites, the rest being supracrustal rocks. The plutonites that were emplaced during the orogeny range from ultramafites to felsic rocks, because magma generation lasted a long period and took place under varying conditions. However, in volume the products of the mafic and ultramafic magmatism were fairly modest, for only 5.9 % of the Svecofennidic plutonites are mafic and ultramafic rocks and 94.1 % felsic rocks. The corresponding figures in the area of the Karelidic formations are 3.3 % and 96.7 %, respectively (Simonen 1980).

The mafic and ultramafic intrusions dealt with in the present study were generated at the climax of the orogeny 1 900—1 860 Ma ago (Papunen & Vorma 1985). Most of the intrusions are located in the Raahe-Ladoga and Ahlainen-Kylmäkoski zones, which have undergone intense movements (Fig. 1). The displacements generated deep-seated fractures that extend to the mantle and along which mafic and ultramafic magma intruded close to the Earth's surface (Gaál 1985). The magmas contained sulphides in variable abundances, resulting in the formation of economic Ni-Cu ores in some intrusions. Similar events took place in the Thompson belt, where the ultramafic intrusions hosting Ni-Cu ores are located in a linear dislocation zone (Peredery 1982).

The Ni-Cu ores generated during the Svecokarelidic orogeny are magmatic ores. These ores, which account for 64 % of world nickel production in 1981, are mainly Precambrian in age and occur in greenstone belts, orogenic belts and cratons (Ross & Travis 1981).

According to the plate tectonic model, the Svecokarelidic orogeny resulted from the collision of two plates. The Archaean craton acted as a passive continental margin, southwest of which the orogeny produced plutonic rocks, geosynclinal formations and island arc volcanics (Gaál 1986).

The eastern part of the Raahe-Ladoga belt is located near the margin of the Archaean craton. The shear zone is therefore attributed to the collision of the Archaean craton with the hypothetical oceanic crust (Gaál 1986). The Karelidic schists are located northeast of the Raahe-Ladoga belt and the Svecofennidic schists and migmatites southwest of it. The Ahlainen-Kylmäkoski belt is far from the Archaean craton, in an area occupied by Svecofennidic schists that is currently considered to represent a marine environment (Huhma 1986).

The genetic history of the rocks studied extends from conditions in the mantle to emplacement and the subsequent crystallization. Therefore, before we can construct an accurate model for the magmatic evolution we must be able to delineate the course of events from partial melting to pre-emplacement and crystallization.

Magmatism was closely associated with tensional forces whose influence extended down to the mantle, since the majority of the intrusions are located in shear zones. Ultramafic magma is generated readily in shear zones, because these zones render the mantle material unstable. The generation of magma is due to a local drop in pressure, which lowers the solidus temperature of the rock. As a consequence, the solidus temperature intersects the temperature of the mantle material and the mantle undergoes partial melting (Oxburgh 1980). As melting proceeds, the density of the material decreases in relation to that of the environment and, as a consequence of isostatic uplift, the melt starts to ascend towards the Earth's surface (Stolper *et al.* 1981).

The basicity of magma depends on the degree of partial melting. Experimental studies have demonstrated that 20 % partial melting produces tholeiitic magma, and about 40 % partial melting komatiitic magma. The composition of the magma also depends on pressure, for the SiO_2 deficiency increases as the pressure increases (Jacques & Green 1980). This holds, however, only on certain conditions, because if the degree of partial melting is high enough the abundance of normative hypersthene increases at pressures exceeding 20 kbar (Thompson 1984).

The P-T conditions prevailing at the formation of magma are, however, mainly controlled by the tectonic environment. The change in the conditions of magma generation is greatest from a marine to a continental environment (Wyllie 1981), with the consequence that opportunities for contamination also increase. On account of contamination, the isotopic compositions of the mantle-derived granitoids change from the Svecofennides towards the Archaean craton (Huhma 1986). The distance between the intrusions and the Archaean craton varies, indicating that during the Svecokarelidic orogeny, mafic and ultramafic magmatism occurred under different geological conditions. Therefore, one of the aims of the present study was to establish the relationship between the magma types and the tectonic environment.

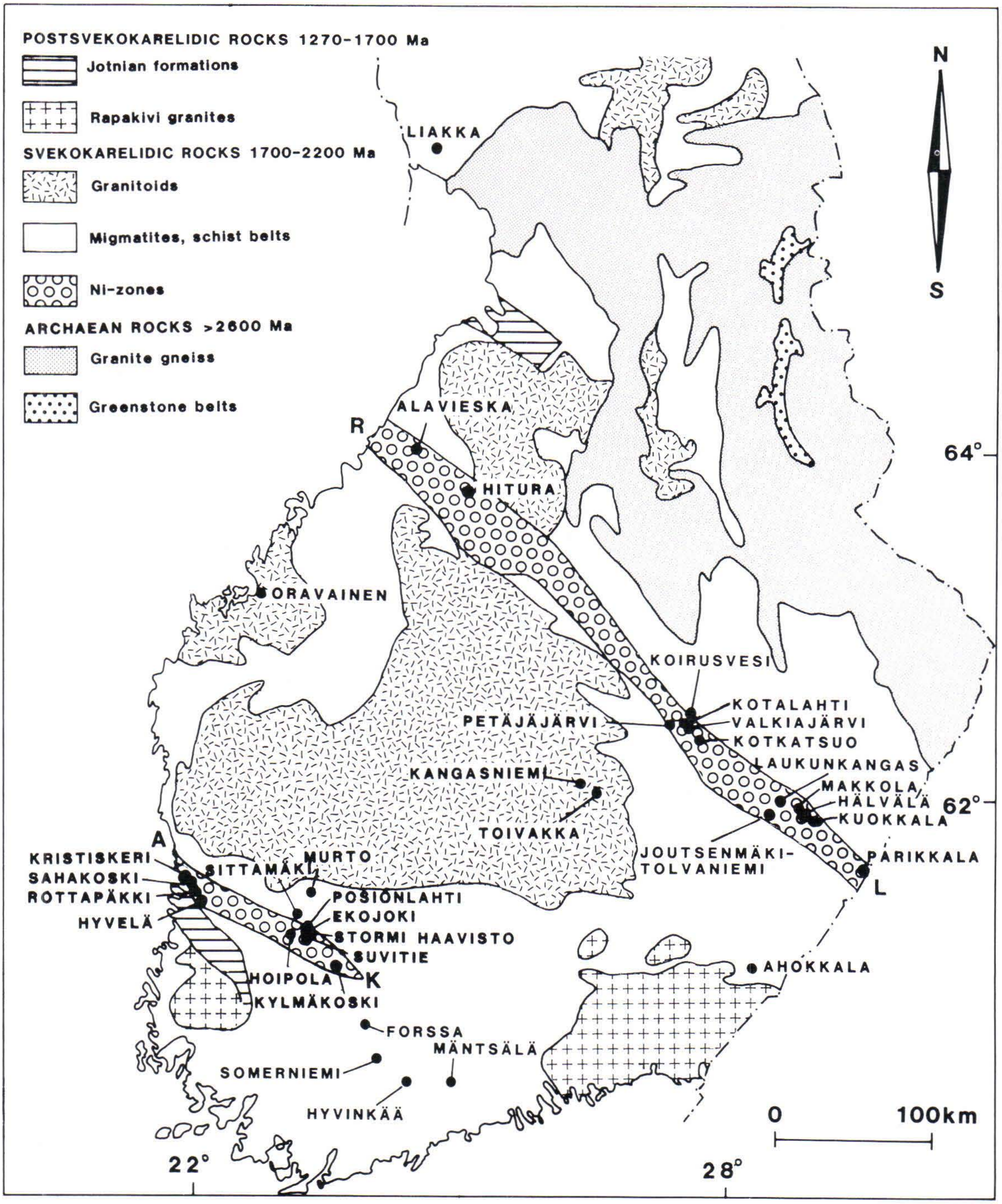

Fig. 1. Location map of the research targets. The nickel zones are marked with codes: RL = the Raahe-Ladoga zone and AK = the Ahlainen-Kylmäkoski zone. Modified from Ketola (1982).

The major elements associated with ore-forming processes behave differently during partial melting. Sulphur behaves like the incompatible elements, i.e. it becomes incorporated in the first melt fractions, whereas nickel enters into the residual phase composed of orthopyroxene or olivine, or both (Sato 1977). The partition coefficients of copper and cobalt between olivine and melt are low. Consequently, at the initial stage of melting, the magma is rich in copper and cobalt in relation to nickel. Therefore the ore potential depends on the degree of partial melting at the beginning of magma formation. It is a well-known fact that ore potential increases parallel to the increase in the basicity of the rocks (Wilson 1981).

The migration of magma to the proximity of the Earth's surface is a complex event, because magmatic activity is characterized by a certain degree of cyclicity. Intrusions and magma pulses derived from one and the same parent magma are often formed during a long time span and under different external conditions. A good example of this is the Stormi intrusion, where oxidizing conditions changed between successive magma pulses (Häkli *et al.* 1979). Hence, an intrusion may contain rocks derived from several magma pulses differing in composition. If the emplacement takes place in pulses, the mantle-derived magma accumulates in a chamber in which it undergoes fractionation and other processes that change its primary composition (O'Hara 1977). The different eruption channels with their source in the magma chamber make their own contribution to the process.

The pre-emplacement stage is perhaps the crucial stage in the ore-forming process, because the sulphides may then fractionate and become concentrated, resulting in the formation of magma pulses of variable sulphide abundance. This is due to the immiscibility of the phases and the difference in their densities, for in many Ni-Cu ore deposits the sulphides were immiscible even before emplacement (Gresham & Loftus-Hills 1981, Page & Schmulian 1981, Williams 1979). The oceanic basalts, too, may be sulphur-saturated at the moment of eruption (Mathez 1976), and Hamlyn *et al.* (1985) have demonstrated that some magmas were already saturated at the time they were formed. Magma may differentiate in similar fashion both before and after emplacement. Therefore, in the present context the factors related to ore potential are dealt with on the basis of differentiation of the intrusives.

In the evolutionary history of a rock the emplacement of magma is followed by crystallization differentiation, in which a homogeneous material produces suites of rocks differing in composition. The compositional gradients are due to changes in mineral abundances and to the variation in the composition of the isomorphic minerals. Because the predominant minerals in the rocks studied — olivine, pyroxenes and plagioclase — are isomorphic minerals their compositions change as the physico-chemical conditions change.

All the rocks studied are cumulates composed of cumulate crystals and intercumulus material filling the interstices. The composition of a momentary cumulate and the mineralogy of the rock suite depend greatly on the mode of fractionation of the magma. If the crystallization proceeds entirely by fractionation, lithological horizons are formed that are mineralogically homogeneous but differ sharply in texture and composition: 'rock hops' are formed (Morse 1980). A good example is the crystallization series from olivine to olivine + plagioclase, which gives rise to a stepwise lithological sequence from dunite to troctolite. Sometimes a system like this is difficult to distinguish from the successive magma pulses differentiated in the magma chamber before the emplacement. On the other hand, the crystallization may proceed partly under equilibrium conditions, resulting in the formation of a rock suite in which the members grade one into the other in mineralogy and composition.

When the crystallization differentiation ends, the composition of the original parent magma can no longer be determined directly, at least not in intrusive rocks. However, it is possible to find portions representing the unaltered parent magma in extrusive rocks. Furthermore, the evolution of the residual melt can be studied from the extrusive rocks directly, but only to a limited extent from the intrusive rocks, from their intercumulus matter. Small portions of the parent magma may have consolidated as a thin layer in the margins of the intrusion, but no efforts were made in the present study to discover them. In principle, the composition of the parent magma can be deduced from the total composition of an intrusive. For the intrusions of the present study, however, this was not feasible because they have been partly obliterated by erosion.

The composition of the parent magma can also be deduced to some extent from regularities exhibited by the crystallization differentiation. This is based on the fact that in the system of two or more components the direction of the crystallization path varies in accordance with the composition of the parent magma, and even the slightest changes in the original composition may change the mineral paragenesis and order of crystallization (cf. Irvine 1970). Even if the parent magmas are close to each other in composition, two different rock suites will crystallize from them if they are located on different sides of the cotectic boundaries. By comparing the order of crystallization of the rocks it is possible to estimate roughly the differences in the compositions of the parent magmas and thereby to evaluate the primary forming conditions.

The composition of the parent magma is also reflected in the earliest cumulate crystals, provided that they represent a phase equilibrated with the most primitive parent magma. The initial composition of the ultramafic magmas is usually evaluated with the aid of olivine, for the calculated Mg value (X_{Mg}) gives the magnesium abundance in relation to that of iron. The method is, however, hampered by the variation in oxygen fugacity and by the subsolidus equilibration of olivine.

3. PURPOSE OF THE STUDY

The study sought to unravel the geological history of the Svecokarelidic mafic and ultramafic intrusions by applying geochemical and petrographic methods. The emphasis was on the processing of geochemical data to delineate the modes of differentiation of the intrusives and to classify their rock types. Owing to the variation in the quality of the data the stress of the discussion on findings is on intrusions containing ultramafic rocks. The results obtained were used to classify the intrusions into types characterized by special modes of differentiation. Attempts were also made to establish the relationship between magmatism and tectonic conditions.

The study also sought to clarify the factors related to the formation of the Ni-Cu ores, the main aim being to establish the changes in the silicate portion that have a bearing on ore potential. The geochemical approach was extended from the level of individual intrusions to a comparison of several intrusions.

4. MATERIAL AND ANALYTICAL METHODS

The material used in the study was selected from that collected for the Outokumpu nickel programme. The total number of samples was 3055, which is about 13 % of all the samples taken for the nickel programme. The sampling has been somewhat biased, because the emphasis of the nickel programme is on the silicate portion of the rocks and samples rich in sulphides have been deliberally avoided. The present study, however, also seeks to unravel the genetic history of the Ni-Cu ores, although the material does not cover the rock suites in the best possible way, because Ni-Cu ores, if any, are characterized by a high sulphur content.

The sampling of the intrusions containing ultramafic rocks was also biased in the sense that pyroxenitic and peridotitic samples are over-represented in relation to gabbro samples. If only a few gabbro samples were taken from an intrusion they were omitted, with the consequence that the crystallization series of the intrusion is shorter than in reality.

The sample densities of the targets also varied markedly. The most representative was the sampling of intrusions containing abundant ultramafic rocks, because they were intersected by drilling. The maximum diameter of the intrusions is often less than one kilometre. The samples taken from large gabbro intrusions cover the intrusions less well, because they represent the present erosional section only. Moreover the relative sampling density was low because some gabbro intrusions have a maximum diameter of several tens of kilometres.

The samples were taken either from the rock surface as hand specimens or from drill cores. The drill cores were sampled at intervals of about 10 m. The samples were split, one half being ground for XRF and AAS analyses, and a polished thin section being cut from the other half for electron microprobe determinations of the minerals. The samples were ground and compressed into briquets for the XRF analysis.

The samples were analysed for 20 elements, i.e. SiO_2, TiO_2, Al_2O_3, Cr_2O_3, FeO, MnO, MgO, CaO, SrO, BaO, Na_2O, K_2O, P_2O_5, ZrO_2, Cu, Ni, Zn, Pb, As and S by XRF at the Geological Laboratory of Outokumpu Oy in Espoo. The samples were also analysed for Cu, Zn, Ni, Co, Pb and Fe incorporated in sulphides by AAS after a selective bromine methanol leach. Sulphur was assayed on an automatic Leco sulphur determinator. Olivine, orthopyroxene, clinopyroxene and amphibole were analysed for Ni and Fe from polished thin sections with an electron microprobe (Häkli *et al.* 1979).

The geochemical material collected for the present study was analysed in 1975—1985. During that period the AAS and electron microprobe techniques remained unaltered. However, not all the samples from certain intrusions were analysed by using the same standard samples. Nevertheless, the correspondence between the samples was considered to be high enough to meet the requirements of the present study because the AAS data on different intrusions were not compared. The electron microprobe data were treated as pooled, however, because the majority of the intrusions was analysed in 1980—1985 during which time the same standard samples were used.

The XRF technique, though, underwent numerous changes, and about one half of the samples were reanalysed by XRF using the same standards and matrix correction programs. Not all the samples analysed after 1982 were reanalysed, because the analytical techniques have remained almost unaltered since that year. Some samples were selected from those analysed after 1982 for reanalysis and the new values were compared with the previous ones. On average, 18 % of the samples were selected from each target for checking. The correction coefficients, which were calculated for the elements of each target, were then used to reduce the analytical data to the same level.

Reanalysis of the samples showed that the changes in level and the scatter in the changes were small. The changes in the abundance level of the major elements were often 0—5 % in magnitude, whereas the changes in the abundance levels of the trace elements were occasionally three-fold; the scatter in the changes was also fairly large. Consequently, whereas the concentration levels of the major elements between different intrusions are comparable, those of the trace elements are less so. The changes in level and the scatter in the changes were particularly high for Pb, As, Cu, Ni, Zn and S and, therefore, these data were not used in statistical analyses. The large deviations in the Pb, As, Cu, Ni, Zn and S abundances may possibly be attributed to the oxidation of sulphur, which has changed the chemical composition of the sample compacts.

The XRF analytical data reduced to the same level were calculated volatile-free and then the sum of the components in each sample was recalculated to 100 %. Since a high abundance of sulphur causes analytical inaccuracy, the samples containing more than 5 % sulphur were omitted. Thereafter sulphur and the iron bound to it were eliminated in accordance with the formula

$$\mathrm{FeO}\% = \mathrm{FeO}_{\mathrm{tot}}\% - 1.7936 \times \mathrm{S}\ \%$$

and each analysis was recalculated to 100 %. The AAS data and electron microprobe data were then pooled with the XRF data. The Fe and Pb analyses were deleted from the AAS data, because they covered only some of the samples. The XRF data cover the whole sample material, but AAS and electron microprobe data are lacking for some intrusions (Table 1).

5. METHODS

1. Data processing

The geochemical data were processed at the University of Turku with a DEC-20 computer provided with a statistics BMDP software package (Dixon 1983). BMDP software was used to plot the scattergrams of two variables (BMDP6D), and to perform the clustering analyses (BMDP2M,BMDPKM), regression analyses (BMDP1R), factor analyses (BMDP4M) and discriminant analyses (BMDP7M). In addition, Fortran programs written at the University of Turku were used to calculate the analyses volatile-free and sulphur-free and to calculate the sliding averages. The norm systems were calculated with the HST package using a VAX computer at the Geological Survey of Finland (Kaivosoja & Koivumaa 1984).

At the first stage of the processing the data on the altered, contaminated and composite rocks were deleted from the analytical data. The elemental abundances of these outliers differ markedly from those of the rest of the population. It is therefore important to delete them from the analytical data because they get disproportionate weight in the correlation matrix and therefore in the factor analyses based on it (Howarth 1983). First the scattergrams of various elements with MgO as the X-axis were studied target by target. A sample was deleted if it exhibited several elemental abundances differing markedly from those in the rest of population. Fifty samples, equalling 1.6 % of the starting material, were deleted.

Next the outliers were deleted by means of the Mahalanobis distance using the BMDP4M program. The Mahalanobis distance is a measure of the separation between two multivariate means expressed in units of the pooled variance (Davis 1973). The anomaly increases with the increase in the Mahalanobis distance, which, thus, is an appropriate means of removing strongly anomalous cases from the population. The outliers were left in the data pool of each target as a separate group. In this way, 485 cases, equalling 15.9 % of the gross material, were discarded.

2. Characteristics of the geochemical data

The differentiation of the intrusions was examined generally on the basis of one or two variables at a time. The variables were selected so that they would describe a certain magmatic event as well as possible. These variables are easy to interpret, provided that they are related to only one event. Magmatic differentiation often involves several events, all of which cause specific variations in the value of the variable. The higher the number of events affecting the differentiation the greater are the difficulties in interpretation based on one variable.

An event may, however, affect several variables simultaneously, giving rise to correlations between the variables. This frequently happens during magmatic differentiation, because the variables of a certain association show strong mutual correlations. Hence, the concentrations of, say, alkali metals correlate positively with each other, as do those of the chalcophile elements. The geochemical data can, therefore, be examined with the aid of the correlations between the variables. Factor analysis is appropriate for this purpose, for it explains the interrelationships of the variables with the aid of factor variables. This approach gives a more reliable picture of the characteristics of the data than does an examination based on one variable only, because the factors describing the events are now related to several primary variables.

3. Application of modelling

An open magma system is one of the basic concepts of petrology. Therefore a system cannot be treated as a single event in which the differentiation proceeds along a liquid line of descent. The open system may have had several simultaneous or successive events that are related to each other in different ways. Hence, when interpreting a system, it is important to be able to identify each event and to associate them with the magmatic evolution.

The processes that take place in an open magma system (e.g. intermixing of magmas and fractional crystallization) can be described with a stepwise model (Bryan 1986). In the model the events are identified and arranged in sequential order with the aid of the geochemical end members. Finally the compatibility of the differentiation model and the lithological sequence is checked computationally.

Similar results are obtained with R-mode factor analysis, in which the factors refer to certain geochemical events. The characteristics of the geochemical events can be studied by interpreting the factors and factor diagrams. The differentiation model can be elaborated by correlating the results of factor analysis with the petrology of the intrusion and the mode of occurrence of the rocks.

4. Classification methods

One of the aims of the study was to group the material. Therefore, the data on each target were submitted to bivariate plots, cluster analysis and factor analysis, making an effort to find petrological counterparts for the geochemical groups. Furthermore, the groups had to be real in the sense that they had to correspond to the multimodal distribution, if any, shown by the factor diagrams.

Various clustering techniques were tested to reach the maximum clustering efficiency. Seven research targets known to differ from each other, at least to some extent, in petrology and composition were selected as a test group. The targets were the intrusives at Oravainen, Sahakoski, Ekojoki, Stormi, Makkola, Kotalahti and Hitura. Forty samples, all representing one and the same lithology, were selected from each target. The Hitura intrusive contains serpentinized dunites. The intrusives at Oravainen and Ekojoki are peridotites with abundant clinopyroxene, and those at Sahakoski and Kotalahti have peridotites rich in orthopyroxene. The Stormi intrusive contains peridotites and that at Makola melanorites.

The samples were classified on the basis of the primary data and the factor scores calculated from them. The factor scores were calculated from the gross data of the test groups in order to establish the influence of the factor scores on the clustering methods, because the clustering based on the factor scores differs from that derived from the primary data. The clustering is different because the new variables (factors) are related orthogonally to each other in the factor space, i.e. they are not intercorrelated.

The test included diverse group combinations. The clustering of the test groups was most successful when based on the factor scores, for then the correctly grouped cases averaged 76 %, while the clustering based on the raw data only grouped correctly in 71 % of the cases.

In the primary geochemical data referring to the magmatic evolution of an intrusion several elements often show strong correlations with each other. For example, the correlation coefficients of the incompatible elements frequently exceed 0.9.

The cluster analysis measures the similarity of the cases with the euclidean distance, which is the distance between the cases expressed as the sum of the differences derived from the standardized variables (Dixon 1983). Moreover, the interrelationship of the variables amplifies the euclidean distance between the cases, resulting in a biased euclidean distance. Therefore the outcome of the cluster analysis can be improved by transforming the raw data so that the variables do not correlate with each other.

5. Comparison of the methods

After the lithological groups had been formed on the basis of the factor scores, the clustering of the cases was studied once again with discriminant analysis of the raw data. Attention was paid to the samples that the discriminant analysis placed in the wrong group. These samples were studied petrographically and then placed in the correct lithological group. Targetwise only a few samples were located in the wrong group, indicating a marked success in clustering. The lithological terminology used was that of Streckeisen (1974) and Papunen *et al.* (1977).

After the samples had been grouped, each study target was submitted to factor analysis, and the factor scores were plotted in the factor coordinate system. The first three factors were used as axes along which the primary variables with loadings exceeding 0.25 in absolute value were also marked. Jöreskog *et al.* (1976) have published examples of similar forms of presentation of the geochemical data.

Factor diagrams are clearly more informative than the bivariate X-Y diagrams frequently used in the presentation of geochemical data. First, there is less compositional overlapping of rock types in factor diagrams than in bivariate diagrams. Therefore the compositional minima between the lithologies indicating fractionation or different magma pulses are more readily recognizable from factor diagrams. Second, events can be examined in the order of their statistical significance, because the factors are arranged in the order of declining percent of variance. Factor analysis also clarifies the interrelationships of several variables, which are difficult to recognize by inspecting only two variables at a time.

According to Howarth (1983), factor analysis can be applied to geochemical data when they are characterized by element associations. This approach is appropriate for the present research data, because the interrelationships of the variables are often high. An advantage of factor analysis is that the dimensions of the primary data can be reduced. Furthermore, the transformed variables (factors) are more reliable than the original variables, because the numerical value of a factor is affected by several primary variables. In this way some of the errors due to the measuring techniques and random events are screened off (Miesch 1981). However, caution should be exercised in interpreting the factor variables, because, as stated above, their values depend on several primary variables (Howarth 1983). The interpretation must also take account of the percentage of total variance attributed to the factors. In the present study the total variance attributed to the first three factors is usually c. 70 %, which is high enough to describe the major events in an intrusion.

All the XRF analyses were normalized to 100 %. Therefore, owing to the constant sum, the major elements exhibit pseudocorrelation (Chayes 1971, Skala 1979). The effect of pseudocorrelation on the interpretation of data was studied by submitting the trace element abundances of some targets to factor analysis, because these elements are free from pseudocorrelation. Comparison of the results with those of the factor analyses based on all the variables showed that the factor patterns resembled each other in spite of the changes in the factor loadings. Biases in the factor loading due to the constant sum result in misinterpretations. To reduce them the interpretation of the factors was extended to include the petrological data.

6. FACTOR GROUPING

This chapter deals with the outcome of factor analysis based on the bulk material. The data on each intrusion were first submitted to factor analysis, after which the factors were compiled into a common data base. The factors of the individual intrusions are dealt with in chapter 7.

The factor data base was submitted to cluster analysis in order to establish the factor types that could represent certain magmatic events. The factors were grouped on the basis of variables with sufficiently high analytical accuracy and communality. The major elements meet both of these requirements, as do the AAS data on Cu, Zn, Ni and Co and the S values. As a rule, the communalities of Cr_2O_3, P_2O_5, MnO and BaO are less than 0.8, meaning that they explain only a small fraction of variance. The MnO communality is low, because MnO does not correlate with any element. The analytical accuracy of MnO is, however, so high that it was included in the cluster variables. The communality of Cr_2O_3 is lowest in the ultramafic rocks, because MgO does not correlate linearly with Cr_2O_3 in the crystallization of ultramafic magma. The crystallization of olivine without the simultaneous crystallization of spinel raises the Cr_2O_3 content in the residual magma whereas the crystallization of pyroxene reduces it. The communality of Cr_2O_3 in gabbros and norites often exceeds 0.8, and therefore it was selected as one of the cluster variables. The grouping of the factors was based on the following variables: SiO_2, TiO_2, Al_2O_3, Cr_2O_3, FeO, MnO, MgO, CaO, SrO, Na_2O, Cu, Zn, Ni, Co and S.

With the aid of the BMDP2M program the factors were grouped into a dendrogram, which shows the similarities between the cases. On the basis of the dendrogram, 13 model groups of factors were formed, which, however, did not include all the factors. The rest of the samples were then placed by the BMDPKM program into the 13 model groups established (Appendix 1). At the end of the table there are a few factor loadings calculated from the XRF data but which were omitted in clustering.

In general, the clustering of the first and second factors was the most successful, whereas the classification and interpretation of the third and fourth factors caused the most confusion. The results also show that, owing to the small amount of data in relation to the size of the intrusion, the factor groups calculated from the data on the gabbro intrusions exhibit the highest heterogeneity. In contrast, the factors extracted from the data on the intrusions containing abundant ultramafic rocks form uniform groups. It can be estimated that, when dealing with data such as these, sufficient stability is achieved with about a hundred samples and/or about a hundred samples are enough to describe an intrusion less than 1 km in diameter.

The groups formed by the factors are called group 1 or factor 1 and so on. The individual factors are not discussed in this chapter. Instead, attempts are made to interpret the factor types and, with them, to describe more general magmatic events.

The event represented by the group 1 factors is a common one and very similar in all the intrusions, because the loadings for many variables are almost the same. The loadings for TiO_2, Al_2O_3, SrO, Na_2O, P_2O_5 and ZrO_2 are usually positive and those for MgO negative. A common feature of the group 1 factors is that the incompatible elements exhibit positive and the compatible elements negative loadings. Judging by the variables, this refers to the crystallization of olivine from ultramafic magma, a supposition that is corroborated by the fact that the group 1 factors were extracted only from the data on ultramafic intrusions. The factors represent intense fractionation of olivine, because the intensity of the fractionation is best reflected in the compatible and incompatible elements (Maaloe 1976). The partition coefficients of the incompatible elements between olivine and melt are very low, with the consequence that the contents of these elements increase in the melt parallel to the increase in the intensity of the fractionation. More than any other event this has changed the composition of magma in almost every intrusion, for the factors of group 1 are, in general, first factors that usually explain 30—50 % of the total variance.

Group 2 has seven factors, in which the loadings for the main elements are high but those for the trace elements are close to zero. Of the trace elements, only Cr_2O_3 and MnO have high loadings. The loadings for SiO_2 and CaO are negative and those for FeO, MnO and MgO are positive. The variables suggest that the group 2 factors are the fractionation of olivine and clinopyroxene. Petrographic observations on the Vammala peridotites show that the olivine crystals are surrounded by intercumulus material composed of clinopyroxene.

Orthopyroxene also occurs, although as a minor constituent. It is likely that the accumulation of olivine was accompanied by the filtration differentiation of intercumulus material, and thus the high loadings for SiO_2 and CaO are due to clinopyroxene. The accumulation of olivine without the simultaneous crystallization of spinel explains the negative loadings for Cr_2O_3 at Ekojoki and Kylmäkoski. The loadings for the main elements are the highest, and hence it is possible that pseudocorrelation has contributed to the loadings on these factors.

Group 3 has six factors with similar loadings for the main elements. The scattering among the trace elements is larger. The loadings for SiO_2, TiO_2, Al_2O_3, CaO and Na_2O are positive and those for FeO and MgO negative. The loadings for MnO and the chalcophile elements are usually negative. The group 3 factors refer to the behaviour of ultramafic rocks and resemble the factors of groups 1 and 2. Consequently, the factors of group 3 are the fractional crystallization of olivine with simultaneous compression of the accumulated olivine crystals. Small amounts of orthopyroxene also accumulated, as shown by petrographical studies.

Group 4 contains by far the highest number of factors. They bear a close resemblance to each other, because the loadings for the elements in different cases are almost identical. The event the factors refer to is a common one that proceeded everywhere in a similar fashion. The loadings for Cu, Ni, Co and S are high and positive. The group 4 factors thus refer to the fractionation of sulphides, which took place fairly independently since the loadings for the lithophile elements are low. The independent behaviour of the sulphides is due to the low viscosity and high density of the sulphide phase. Deformation may remobilize crystallized sulphides, a factor that emphasizes the special character of the sulphides. The abundances of Al_2O_3, MnO and MgO exhibit a certain regularity in relation to that of the sulphide phase, because in four cases Al_2O_3 has a negative loading, in five cases MnO has a positive loading and in six cases MgO has a positive loading, suggesting that the sulphides prefer the most mafic and least differentiated rocks of the intrusions.

The event described by group 5 is a common one, for the group has fifteen factors, most of which were extracted from the data on mafic intrusions. A common feature of the factors is that the loadings for TiO_2, FeO, MnO and P_2O_5 are high and positive and those for SiO_2 negative. The loadings for Al_2O_3 and other incompatible elements are rather often negative. The positive loadings for FeO, MnO and TiO_2 refer to the crystallization of the Fe-Ti oxides. The negative loadings for Cr_2O_3 show that chromium prefers the silicate phase. An interesting finding is that P_2O_5 has positive loadings at the same time as TiO_2, FeO and MnO. Apatite obviously crystallized together with the oxides, because the Kristiskeri and Joutsenmäki—Tolvaniemi intrusions, for example, have accessory apatite. The crystallization of apatite is promoted by the increase in SiO_2 content as well as by the falling temperature (Watson 1979). The loadings for SiO_2 are almost invariably the reverse of those for FeO, because these elements behave in different ways in the fractionation of mafic magma (Morse 1980). The loadings for the other incompatible elements are occasionally positive, although without any regular pattern.

There are ten factors in group 6. The loadings for Al_2O_3 and Na_2O are most often negative and those for Cr_2O_3, MgO and Ni positive. The loadings for TiO_2 are fairly regularly negative and those for Co positive. The loadings for MgO, Cr_2O_3, Ni and Co refer to the fractionation of orthopyroxene, but in some cases, CaO refers to clinopyroxene. As suggested by the negative loadings for Al_2O_3 and Na_2O, plagioclase fractionated at the same time. The negative loadings for TiO_2 and other incompatible elements refer to the enrichment of residual melt in these elements.

In the group 7 factors the loadings for MgO, Cr_2O_3, FeO and MnO are usually negative, whereas those for Al_2O_3, SrO, Na_2O, P_2O_5 and ZrO_2 are positive. Plagioclase and pyroxenes were the fractionating minerals. However, it is not possible to interpret group 7 unequivocally because it includes factors extracted from the data on intrusions that contain mafic and ultramafic rocks. Furthermore, the loadings for many elements vary considerably. As far as the mafic intrusions are concerned, however, the group 7 factors can be considered as the fractionation between plagioclase and pyroxene. In ultramafic intrusions, the factors refer to the enrichment of residual melt in incompatible elements.

The factors in group 8 resemble those in group 7. The loadings for MgO and CaO are negative and those for SiO_2, TiO_2, BaO, Na_2O, K_2O, P_2O_5, ZrO_2 and Zn positive. Noteworthy are the high loadings for Zn together with those for the incompatible elements. Accordingly, Zn was enriched during a late stage of crystallization. Better than anything else the group 8 factors refer to the fractionation of clinopyroxene from the gabbro magma and the enrichment of the residual melt in the incompatible elements. The group 8 factors are often the first factors explaining 16—41 % of total variance.

The loadings for CaO in group 9 are negative and those for SiO_2, BaO, K_2O, P_2O_5 and ZrO_2 positive. The loadings for the other variables fluctuate considerably. Therefore the events to which the factors refer are probably rather different, as is also suggested by the fact that the group 9 factors are related to the intrusions containing both mafic and ultramafic rocks. The heterogeneity of the group 9 factors can also be attributed to the fact that they are third or fourth in order. As to ultramafic intrusions, the group 9 factors probably indicate the fractionation of clinopyroxene and the enrichment of the residual melt in incompatible elements. For mafic intrusions, the question concerns a similar event, although occasionally plagioclase has been the fractionating mineral, because Al_2O_3, too, shows negative loadings.

Group 10 totals 4 factors. All of them have positive loadings for Al_2O_3, CaO and SrO, and negative loadings for FeO and MnO. Occasionally SiO_2 and K_2O, too, exhibit negative loadings. The highest loadings, on average, are those for CaO, SrO and Al_2O_3. Therefore, the group 10 factors can best be interpreted as the crystallization of plagioclase. The loadings for FeO and MnO suggest that the behaviour of plagioclase was the reverse of that of the mafic minerals. Considering the above combinations of variables it is not possible to attribute the negative loadings for SiO_2 and K_2O to normal crystallization differentiation. Hence, they probably refer to contamination contemporaneous with crystallization.

The loadings for MgO in the group 11 factors are negative and those for SiO_2, TiO_2, BaO, K_2O, P_2O_5 and ZrO_2 positive. The loadings for SrO and Na_2O are less often positive. The loadings for Zn are sometimes high, but the signs vary randomly. The factors in group 11 resemble those in group 1, which refer to the fractional crystallization of olivine. The most significant difference between them is in the loadings for Al_2O_3. Both factors may refer to similar events but in different environments. The group 11 factors were extracted from intrusions in which plagioclase appeared as a liquidus phase at a fairly early stage. Such intrusions are Sahakoski, Laukunkangas and Koirusvesi. In contrast, the factors in group 1 were extracted from data on intrusions containing only small amounts of plagioclase-bearing late differentiates. The exceptional factor loadings of Murto and Ahokkala are attributed to the small body of data.

There are seven group 12 factors and they all resemble each other a great deal. Almost all the incompatible elements show positive loadings, only those for TiO_2 and P_2O_5 being close to zero. The loadings for Al_2O_3, CaO, SrO and Na_2O are particularly high, referring to the abundance of plagioclase in the rocks, whereas the high negative loadings for Cr_2O_3, FeO, MnO and MgO are due to the abundance of olivine and pyroxenes. In addition, chalcophile elements occasionally exhibit negative loadings. The variables suggest that the group 12 factors refer to the fractionation of plagioclase, pyroxenes, olivine and, sometimes, of sulphides during crystallization. The total variance of these factors is considerable, and they refer to extensive events in the intrusions. As shown by Makkola, Laukunkangas, Valkiajärvi and Koirusvesi, the factors do not always refer to the fractional crystallization of plagioclase and mafic minerals but to two separate magma pulses. The crosscutting relations between an older and a younger magma pulse are visible in the intrusions of Laukunkangas and Valkiajärvi. One pulse is peridotite, pyroxenite or melanorite in composition and the other is either norite or gabbro. The observations on the Sahakoski intrusion show that peridotites and norites constitute a continuous crystallization series.

Only a few elements in the group 13 factors show high absolute values for loadings. The loadings for Al_2O_3 are positive and those for Cr_2O_3 and MgO negative. Occasionally the loadings for the incompatible elements are positive and those for chalcophile elements negative. Judging by the variables, the group 13 factors represent the fractionation of orthopyroxene and the residual melt. The small number of variables with significant loadings on these factors is due to the fact that the factors are second, third or fourth and thus have a low percentage of explained variance. Therefore, the factors of group 13 refer to small-scale events, which, however, differ from intrusion to intrusion, as shown by the irregularity in the loadings for several elements. The events represented by the group 13 factors occurred in the intrusions that contain mafic or ultramafic rocks. Hence, the factors lack a clear geological background.

7. DESCRIPTION OF THE STUDY TARGETS

1. General

This chapter describes, with the aid of factor analysis, the geological events the intrusions have undergone. On account of variations in the data the factor diagrams are given only for the targets that are important for the present study or on which there are abundant data. The factor diagrams of the other targets were omitted, although their description, too, is based on factor analysis. Table 1 shows the form of presentation, number of lithological groups and rock types of the intrusions. Appendix 2 lists the average compositions of the rocks by intrusion. Each target is provided with a location code number.

Figure 1, which illustrates the regional distribution of the intrusions, shows that they are areally clustered. Therefore, the intrusions were divided into groups on the basis of their areal and geological location.

The areal clustering of the intrusions is most distinct in the zones of Ahlainen-Kylmäkoski and Raahe-Ladoga. The intrusions of Kristiskeri, Sahakoski, Hyvelä and Rottapäkki in the western part of the Ahlainen-Kylmäkoski zone constitute an areally rather restricted group. The intrusions of Murto, Sittamäki, Hoipola, Posionlahti, Ekojoki, Stormi, Haavisto, Suvitie and Kylmäkoski in the eastern part of the Ahlainen-Kylmäkoski zone form another areal group. Around the lake Haukivesi in the Raahe-Ladoga zone there are several intrusions within a small area constituting an areal group that includes the intrusions of Laukunkangas, Makkola, Hälvälä, Kuokkala and Joutsenmäki-Toivaniemi. Another intrusion cluster in the Raahe-Ladoga zone is located in the Kotalahti area and contains the intrusions of Koirusvesi, Petäjäjärvi, Kotalahti, Valkiajärvi and Kotkatsuo. There are no other study targets near the intrusions of Alavieska, Hitura and Parikkala in the Raahe-Ladoga zone, and hence these intrusions have been treated as areally individual intrusions. The same applies to the intrusions of Oravainen, Ahokkala and Liakka.

The gabbro intrusions of Forssa, Somerniemi, Hyvinkää and Mäntsälä in the schist area of southern Finland constitute a fairly coherent group.

The intrusions of Toivakka and Kangasniemi are located in the area of the central Finland granite batholite and have therefore been treated as an individual group.

Table 1. Information on the intrusions in columns. Column 1: name of intrusion. Column 2: location code. Column 3: number of lithological groups formed from the material of the intrusion. Column 4: total number of samples. Column 5: rock types in the intrusion. Column 6: XRF data available on target. Column 7: AAS data available on target. Column 8: electron microprobe data available on target. Column 9: data on target presented in factor diagrams. The rock types in column 5 have the following codes: 1 = dunite, 2 = lherzolite, 3 = olivine websterite, 4 = websterite, 5 = harzburgite, 7 = olivine norite, 8 = melanorite, 9 = norite, 10 = leuconorite, 11 = gabbronorite, 12 = leucogabbronorite, 13 = amphibole gabbro, 14 = olivine gabbro, 15 = diorite, 16 = quartz diorite, 17 = cortlandite.

1	2	3	4	5	6	7	8	9
Oravainen	02	3	92	1, 2, 3, 4	×	×	×	×
Kristiskeri	04	3	51	9, 11, 12	×	×	×	
Sahakoski	06	5	167	2, 5, 8, 9	×	×	×	×
Hyvelä	09	1	26	9, 13	×			
Rottapäkki	10	1	41	2, 9	×	×		
Murto	12	2	17	2	×	×	×	
Sittamäki	14	2	24	3	×	×	×	
Hoipola	16	4	91	2, 4	×	×	×	×
Posionlahti	18	3	51	1, 2	×	×	×	×
Ekojoki	20	3	56	2	×	×	×	
Stormi	24	4	119	1, 2, 17	×	×	×	×
Haavisto	28	3	43	2, 3	×	×	×	
Suvitie	30	3	31	2, 3, 4	×	×		
Kylmäkoski	32	3	80	2, 3, 4	×	×	×	×
Somerniemi	34	3	47	13, 15, 16	×	×	×	
Forssa	36	3	75	13, 15, 16	×	×	×	
Hyvinkää	38	3	58	13, 15, 16	×	×	×	
Mäntsälä	40	2	50	13, 15, 16	×	×	×	
Ahokkala	42	2	35	9, 13, 15	×	×	×	
Parikkala	44	2	62	9, 13	×	×	×	×
Joutsenmäki—Tolvaniemi	46	2	335	13, 15, 16	×	×	×	×
Kuokkala	48	1	44	13	×	×	×	
Hälvälä	50	3	60	9, 10	×	×	×	
Makkola	52	5	149	9, 11	×	×	×	×
Laukunkangas	54	5	95	2, 7, 9, 11, 13	×	×	×	
Laukunkangas	55	5	260		×			×
Valkiajärvi	56	3	76	11, 12	×	×	×	
Kotalahti	58	3	68	2, 4	×	×	×	×
Petäjäjärvi	60	2	36	5	×		×	
Kotkatsuo	62	3	80	8, 9, 10	×		×	
Koirusvesi	64	4	79	1, 2, 4, 10, 11	×	×	×	×
Hitura	66	3	85	1, 2	×	×		×
Alavieska	68	3	56	11, 13	×	×	×	
Liakka	70	4	153	3, 4, 11,	×	×	×	×
Toivakka	72	4	62	13, 14, 15	×	×	×	
Kangasniemi	74	1	27	13, 14, 15	×	×	×	

2. Oravainen environment

The ultramafic intrusion of Oravainen is located in the area of the Vaasa granite, which is a migmatic and synorogenic gneiss granite (Isohanni 1985). The intrusion contains about 1.3 M.t. of ore assaying 0.95 % Ni and 0.16 % Cu. The gneiss granite exhibits abundant sedimentary or volcanic biotite-plagioclase gneiss inclusions. In the Oravainen area the Vaasa granite is predominantly kinzigitic gneiss granite recrystallized under granulite facies conditions. Granitization has resulted in the formation of a dome structure in which the metamorphic grade in-

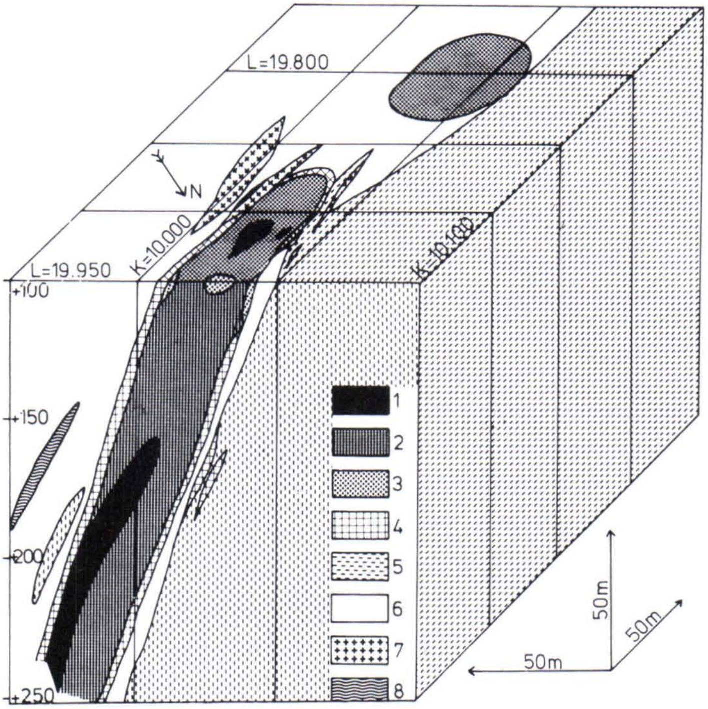

Fig. 2. Block diagram of the Oravainen intrusion after Isohanni (1985). 1 = massive ore + metadunite, 2 = lherzolite, 3 = websterite, 4 = hornfels, 5 = pyroxene quartz diorite, 6 = kinzigitic gneiss granite, 7 = pegmatitic granite, 8 = migmatitic mica gneiss + graphite gneiss.

creases towards the margins. The Oravainen ultramafic intrusion is located in a zone of moderate granitization. Adjacent to the ultramafite there are some quartz diorite and quartz-hypersthene gabbros as fragments in kinzigite.

Oravainen (02)

The Oravainen intrusion is composed of two tubular parts in association with each other, as demonstrated by the latest drilling data (T. Huhtala, pers. comm.). Consequently, the data were treated as one entity. The intrusion pipes are petrologically concentric, and the dunitic core grades outwards via lherzolites into websterites (Fig. 2).

The Oravainen intrusion consists of three lithological groups. The rocks of groups 1 and 2 are lherzolites and dunites with mainly olivine and orthopyroxene. Clinopyroxene occurs as an intercumulus mineral or as subhedral crystals. The rocks of group 3 are clinopyroxene-predominant websterites. Similar websterites occur in the Vammala area.

The samples of group 1 show high factor scores along factor 2, which is the sulphide mineralization factor (Fig. 3). Apart from slight grading, the samples differ markedly from the other lithologies in composition. According to factor 2, the crystallization of chromite was associated with the fractionation of the sulphides. Groups 2 and 3 constitute an almost continuous series along factor 1, which refers to fractionation between olivine, orthopyroxene and clinopyroxene. On account of its high clinopyroxene abundance, group 3 shows negative factor scores.

The Oravainen lherzolites are anomalously high in incompatible elements. The compositions of the lithologies are also unusual in that some parts of the lherzolites have more SrO, BaO and

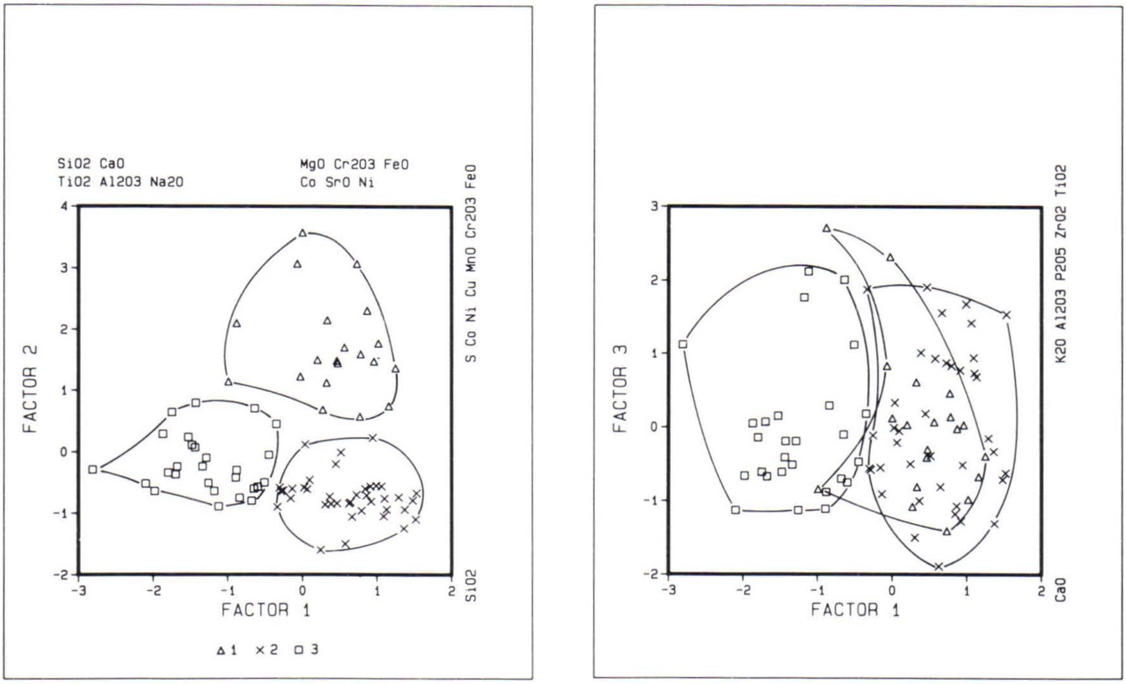

Fig. 3. Factor scores of the Oravainen data. The rocks are divided into three groups: 1 = lherzolites with abundant sulphides, 2 = lherzolites poor in sulphides and 3 = websterites. The loadings for the elements marked in this diagram and in the other similar diagrams are given in Appendix 1.

K_2O than do the websterites. The abundances of these elements are shown along factor 3, where the distribution of the lherzolites differs from that of the websterites. Factor 3 refers to contamination, because, during normal crystallization differentiation, the abundances of BaO and K_2O cannot decline while basicity decreases.

Isohanni (1985) divided the ultramafic rocks into three major groups: dunites, lherzolites and websterites. The Al_2O_3 and alkali metal contents of lherzolites exhibit three clusters (see Isohanni op. cit.). Group 3 of the present study and the websterites of Isohanni correspond to each other, but groups 1 and 2 include both lherzolites and dunites. Both studies have revealed high K_2O contents in lherzolites, which Isohanni, too, attributes to contamination.

Since some of the lherzolites are contaminated the magmatic evolution must have varied strongly within the intrusions. The websterites differentiated mainly from the uncontaminated lherzolites, as shown by their low K_2O values. Contamination promotes the segregation of sulphides, because alkali metals increase FeO activity and thus reduce the solubility of sulphides (Shimazaki & Clark 1973). Nevertheless, contamination had only a slight effect on mineralization (see chapter 11). The sulphides were segregated effectively as shown by factor 2, which has a rather distinct bimodal distribution.

3. Pori-Ahlainen environment

The targets in the Pori-Ahlainen environment are composed of lherzolites and norites, and the most marked Ni-Cu mineralizations occur in the intrusions of Hyvelä and Sahakoski. At Hyvelä

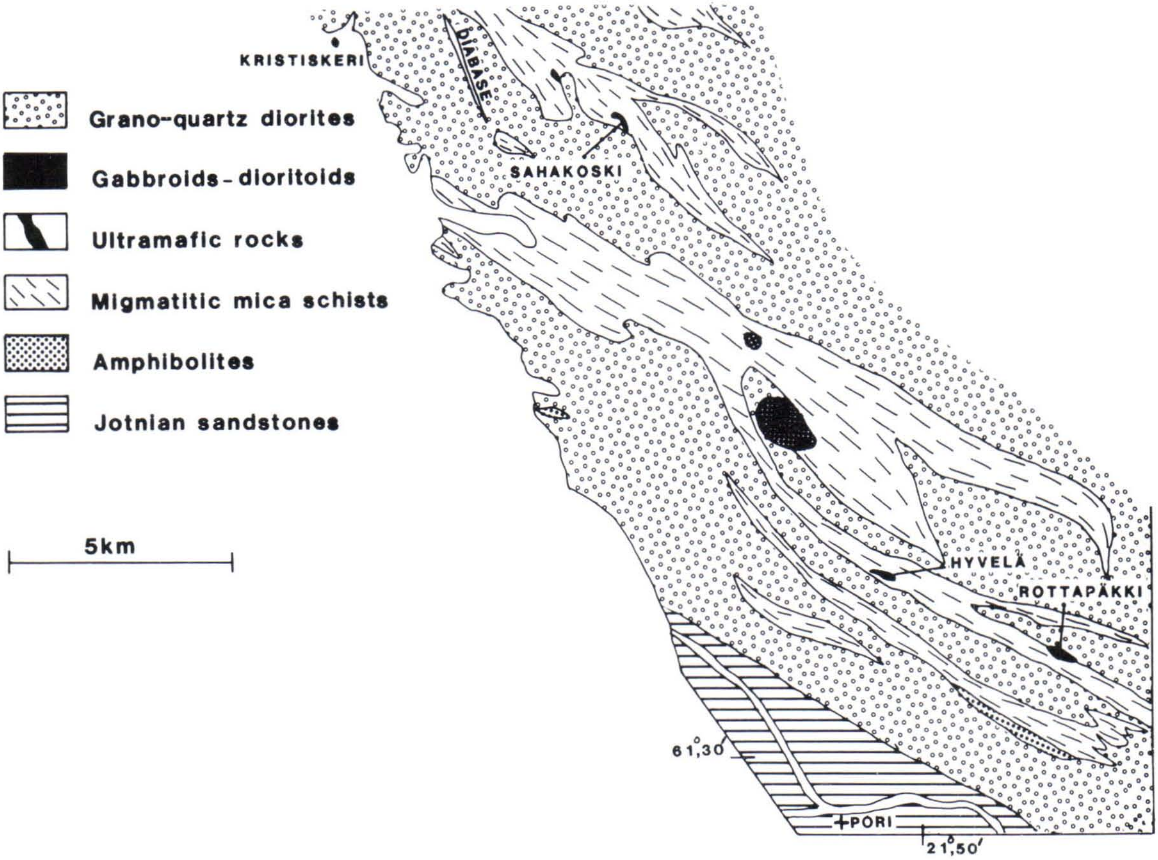

Fig. 4. Geological setting of the Pori and Ahlainen environment. The centre of Ahlainen village is about 1 km north of the northern edge of the map. The map is based on geological mapping undertaken by Outokumpu Oy.

there are about 800 000 t of ore, assaying 0.52 % Ni and 0.26 % Cu (Stenberg & Häkli 1985). Sahakoski has been estimated to contain about 1 M.t. of ore, grading 0.79 % Ni and 0.26 % Cu (Mäkelä 1984). Small sulphide mineralizations also occur in the Kristiskeri intrusion.

The supracrustal rocks in the area are mica gneisses, kinzigites, skarn rocks, graphite gneisses and amphibolites, with mica gneisses as the predominant rocks (Fig. 4) (Mäki 1980). In places, e.g. adjacent to the Hyvelä intrusion, the mica gneisses grade into kinzigites. Graphite gneisses and skarns occur as interlayers in the kinzigites and mica gneisses. Amphibolite of sedimentary origin also occurs as interlayers of varying thickness. More massive amphibolite portions in the east and west of the study area are interpreted to be volcanic in origin.

The plutonic rocks are predominantly synorogenic granodiorites and quartz diorites, which occur as parallel intrusion zones. The quartz diorites contain hornblende gabbros and hornblendites as breccia-like early segregated bodies. In places there are continuous zones of hornblende gabbro.

Intense isoclinal folding took place in several phases, because here and there the mica gneisses grade into schollenmigmatites with hornblendite inclusions. At Ahlainen and Pori movements have divided the bedrock into blocks between which the structures and grade of metamorphism occasionally change sharply (Seitsaari 1962). The intrusions studied are located in a block whose eastern edge is bounded by the Kynsikangas fault zone.

Kristiskeri (04)

The Kristiskeri intrusion measures c. 150 × 200 m, and its greatest depth is c. 140 m. The intrusion has three lithological groups. The rocks of group 1 are norites and gabbronorites with orthopyroxene, plagioclase and amphibole; clinopyroxene is a minor constituent. These rocks grade petrologically into the gabbronorites and leucogabbronorites of group 2. The group 3 rocks are leucogabbronorites with plagioclase as cumulus mineral. Three lherzolite samples were also collected from the intrusion but they were omitted from data processing; they are included in group 1.

Group 1 occurs in drill intersections as continuous portions. In two intersections it constitutes the upper part of the intrusion with the superimposed groups 2 and 3 below it. The mode of occurrence of the rocks suggests that the Kristiskeri intrusion was formed by two magma injections. The rocks of groups 2 and 3 intruded first, followed by the more mafic rocks of group 1. However, apart from CaO, Cr_2O_3 and MgO, the compositions of groups 1 and 2 are so similar that they can be considered comagmatic.

Sulphides were segregated during all the crystallization stages. Segregation was not, however, extensive, because samples with high sulphide contents are rare. The fact that some samples exhibit high sulphide abundances demonstrates local high-intensity mineralization (Appendix 2).

Sahakoski (06)

The plate-like intrusion of Sahakoski measures c. 240 × 50 m on the surface, but widens with depth, although its full depth extent has not been established; the deepest drill intersections extend to 650 m. The plate-like upper portion of the intrusion is composed of lherzolites underlain by norites. The contacts are gradational and in places the rocks exhibit interfingering contacts.

The Sahakoski intrusion consists of five lithological groups. Groups 1 and 2 are lherzolites, which grade into harzburgites and melanorites. The cumulus minerals are olivine and orthopyroxene, and the intercumulus ones clinopyroxene and sometimes plagioclase. Groups 4 and 5 are norites. Group 3 contains both norites and lherzolites.

All groups are shown in Fig. 5a. Factor 1 discriminates best the norites from the lherzolites. Factor 1 has the highest loadings for MgO, Cr_2O_3, FeO, Na_2O, CaO, SrO, Al_2O_3 and SiO_2, indicating that the difference in composition between the rocks is due to the fractionation of plagioclase and mafic minerals. Observations on the intrusion suggest that lherzolites and norites are from the same crystallization series (J. Vesanto, pers. comm.). Group 3 has high scores of factor 2, ascribed to the abundance of sulphides.

To accentuate the relations between the other groups, group 3 was not included in Fig. 5b. Groups 1 and 2, which are composed of lherzolites, form a coherent entity although they exhibit grading into norites. As in Fig. 5a, factor 1 is the fractionation of plagioclase and mafic minerals. Factor 2 refers to the enrichment of the residual melt in incompatible elements. Accordingly, the rocks of group 2 are more highly evolved than those of group 1.

Orebody A is located between lherzolites and norites (Mäkelä 1984). Some of the samples of group 3 derive from orebody A but the majority exhibits a mode of occurrence similar to that of the rocks in orebody A, i.e. they occur in a contact between lherzolites and norites. When norites occur as interlayers in lherzolites or vice verse, they are often sulphide-bearing.

Although sulphides occur in both lherzolites and norites, the lherzolite-norite association has the highest ore potential. According to Fig. 5b, group 3 is closer to lherzolites than to norites and therefore the sulphides probably derived from lherzolites. Petrographic observations show that

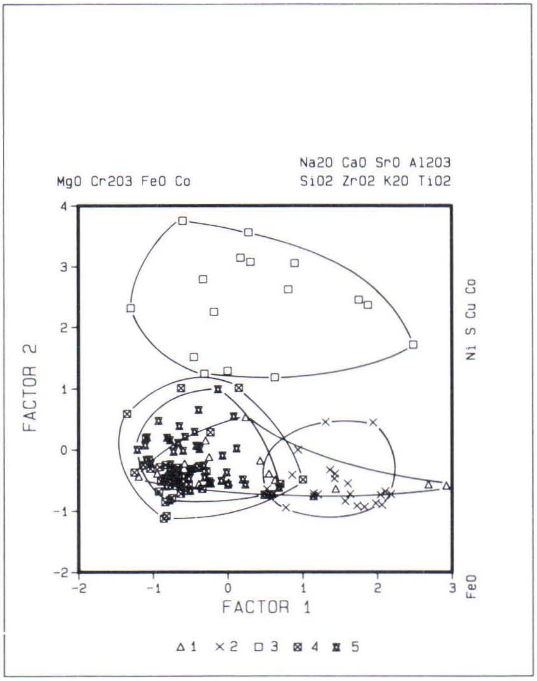

Fig. 5a. Factor scores of the Sahakoski data. 1 and 2 = lherzolites poor in sulphides, 3 = lherzolites and norites rich in sulphides, 4 and 5 = norites.

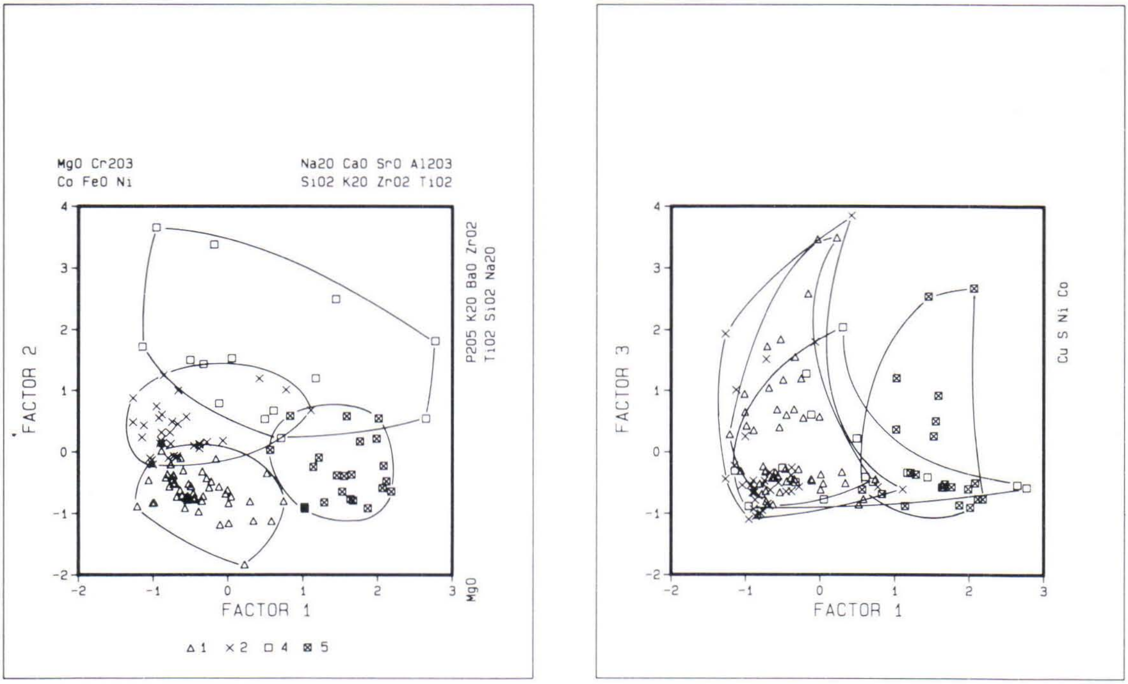

Fig. 5b. Factor scores of the Sahakoski data with the lherzolites and norites rich in sulphides (Group 3 in the previous figure) deleted. 1 and 2 = lherzolites poor in sulphides, 4 and 5 = norites poor in sulphides.

lherzolites are richer than norites in disseminated sulphides.

Hyvelä (09)

The Hyvelä intrusion is a platy body some 400 m long varying in thickness from 20 to 100 m. The Hyvelä data do not show compositional clustering. The rocks are mainly norites and cummingtonite gabbros and they have been treated as a single group (Appendix 2).

According to Mäki (1982), the Hyvelä intrusion is concentric in composition and petrology. The most mafic lithologies (norites) are located in the middle of the intrusion, grading into more silicic rocks (cummingtonite gabbros). Two sulphide-rich occurrences in the intrusion show that the magma was sulphide-saturated at the time of emplacement (Stenberg & Häkli 1985).

Rottapäkki (10)

The data on Rottapäkki were collected from three adjacent massifs, of which the middle one is the largest (100×250 m) (Haga 1986). The rocks are lherzolites composed of olivine, orthopyroxene and clinopyroxene. The lherzolites are underlain by small portions of norites but they have not been included in the present data. The data did not show geochemical clustering and were thus not grouped lithologically. The target exhibits sulphides only sporadically (Appendix 2).

4. Vammala environment

In the environment of Vammala there are numerous mafic and ultramafic intrusions with varying amounts of sulphides (Fig. 6). The ultramafic intrusions have only a little gabbroic rock, and as a rule the gabbros, which grade into quartz diorites, occur as separate intrusions.

The most important Ni-Cu occurrence is hosted by the Stormi intrusion and contains 18 M.t. of ore, grading 0.32 % Cu and 0.43 % Ni (Häkli *et al.* 1979). Promising Ni-Cu occurrences have also been encountered in association with the intrusions of Ekojoki and Posionlahti. Small mineralizations occur in almost all intrusions either in their vertical contacts or at the base. Lherzolites are by far the most interesting rocks in terms of ore geology. Cortlandites are the least ore-potential rocks in the area. The Kylmäkoski intrusion is included in the intrusions of the Vammala environment, because of the similarities between its lithologies and country rocks and those in the Vammala area. About 700 000 t of ore, assaying 0.55 % Ni and 0.48 % Cu, was mined from the Kylmäkoski intrusion (Papunen 1985).

The ultramafites in the area are located in the southern part of the Tampere schist belt, which is characterized by geosynclinal sediments. The sedimentary rocks have metamorphosed into veined gneisses. The gneisses have amphibolite, uralite porphyry and plagioclase porphyry interlayers and other layers rich in carbonate. Gneisses grade into kinzigites, which contain garnet, cordierite and sillimanite. Graphite gneisses often occur with the kinzigites (Heikkilä-Harinen 1975, Häkli & Vormisto 1985). Granodiorites and quartz diorites are the predominant plutonic rocks. Ultramafites occur in mica gneisses as separate bodies of varying shape.

The presence of amphibolite and carbonate-bearing fragments of folds of various size embedded in mica gneisses indicate that the area has undergone intense folding (Mäkinen 1984). Schollenmigmatites with fragments of mafic gneisses or plutonic rocks embedded in quartz dioritic or tronhjemitic matrix abound in the Vammala area.

Murto (12)

The study target is composed of four adjacent

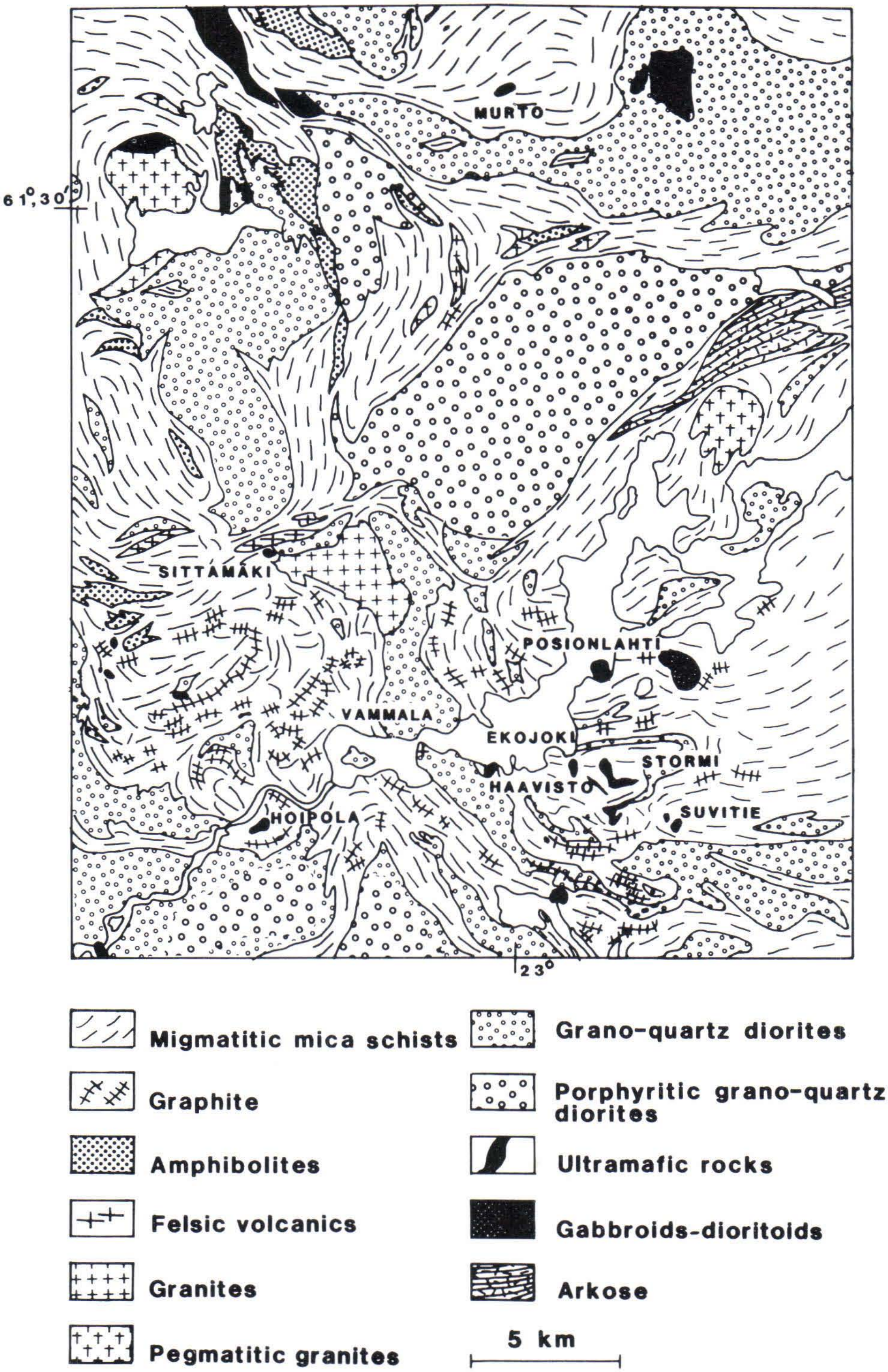

Fig. 6. Geology of the Vammala environment. Modified from Aarnisalo et al. (1982) and Matisto (1971).

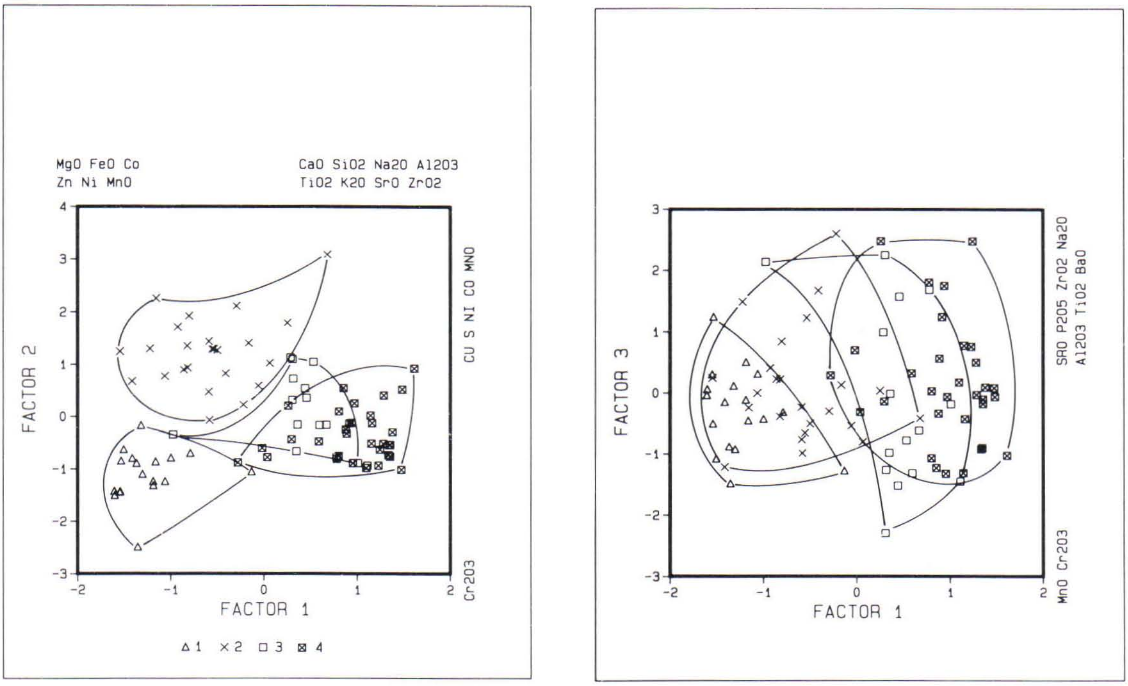

Fig. 7. Factor scores of the Hoipola data. 1 and 2 = lherzolites, 3 and 4 = websterites.

intrusions extending no deeper than 50—100 m. The diameter of the largest intrusion is c. 300 m (Pehkonen 1983a). The intrusions include lherzolites that contain olivine, orthopyroxene and clinopyroxene. Only 17 samples were taken from the target and hence the data were treated as one entity. The intrusions do not differ in composition. The data were clustered into two lithological groups, of which the more mafic is richer in olivine. No marked sulphide abundances have been encountered in the intrusions (Appendix 2).

Sittamäki (14)

The Sittamäki intrusion is circular in shape and has a diameter of c. 300 m. Down to a depth of c. 200 m it is composed of olivine websterites and from there down to 300 m of gabbros (Pehkonen 1983b). The samples of the present study, which were taken from the olivine websterites only, contain olivine, orthopyroxene and clinopyroxene. The olivine websterites were divided into two groups, of which the more mafic one is richer in olivine. In relation to the general level, the Sittamäki intrusion is poor in sulphides (Appendix 2).

Hoipola (16)

The Hoipola intrusion is a cup-like body with a diameter of about 300 m. Its greatest established depth is c. 250 m. The intrusion constitutes four types of rock. The rocks of groups 1 and 2 are lherzolites composed of olivine, orthopyroxene and clinopyroxene, and the rocks of groups 3 and 4 are websterites, with orthopyroxene and clinopyroxene and occasionally olivine as essential minerals. The intrusions also have small amounts of gabbros, which, owing to the small number of samples, were not included in the present study.

All the factor variables of group 1 plot within a small area (Fig. 7). Since the MgO content is also high the group represents olivine-orthopyroxene cumulates. Group 1 is not mineralized, because its factor 2 scores are low. Factor 1 reflects the degree of evolution of the rocks and shows that the grade of differentiation increases in the order 1, 2, 3 and 4. Olivine and clinopyroxene were the minerals that experienced the strongest fractionation during differentiation.

Groups 2, 3 and 4 cover almost equal compositional areas along factor 3, which refers to the enrichment of residual melt in incompatible elements. The mafic minerals exerted only a slight influence, because the loadings for Cr_2O_3 and MnO are low.

Groups 3 and 4 resemble each other, for they plot in the same area along the first three factors. Together they constitute the major part of the Hoipola intrusion. Group 3, which is richer in sulphides, is oriented more along factor 2 than is group 4. The groups also differ in values of SiO_2, FeO, CaO, BaO and K_2O (Appendix 2).

Lowermost in the intrusion are the rocks of group 2, which are overlain by the rocks of groups 1, 3 and 4. Since differentiation cannot proceed from the most silicic to the most mafic rock, the rocks of groups 1 and 2 represent different magma injections. Factor 2 reflects mainly the difference between the rocks of the two magma injections and so cannot be interpreted as a simultaneous fractionation of sulphides and chromites. The rocks of groups 3 and 4 may represent the third magma injection. Group 3 is rich in K_2O and therefore obviously derived from group 4 through contamination.

Posionlahti (18)

The Posionlahti intrusion is a roundish body about 1 km in diameter, extending to a depth of c. 350 m (Pehkonen 1983c). The intrusion has three lithological groups. The rocks of groups 1 and 2 are lherzolites and dunites rich in chromite and completely serpentinized. The rocks of group 3 are lherzolites composed of olivine, orthopyroxene and clinopyroxene.There are gabbros in the margins of the intrusion but they were not included in the present study.

As shown by factor 1, groups 1 and 3 contain some strongly fractionated samples (Fig. 8). Factor 2 refers mainly to the fractionation of olivine and orthopyroxene, and the boundary between groups 1 and 2 was set perpendicular to that factor. The groups belong to the same crystallization series, since there is no concentration minimum between them.

According to factor 3 the samples of group 3 have less FeO and more SiO_2 and CaO than do the samples of the other groups. The difference might be attributed to the abundance of clinopyroxene in relation to that of olivine and orthopyroxene. Group 3 is the most heterogeneous in composition.

In places the groups overlap, but the rocks of group 1 located in the upper part of the intrusion constitute the most coherent entity. The rocks of group 3 are located at the base of the intrusion. The relationship between the groups indicates that the Posionlahti intrusion was formed by at least two magma injections. Group 3 was emplaced first because it occurs at the base of the intrusion. Thereafter the more mafic groups, 1 and 2, intruded at higher levels. Hence factor 3 refers to the differences between the members of a discontinuous series rather than the continuous crystallization of the intrusion. No mineralization occurred in groups 1 and 2, as revealed by the low contents of Ni, Cu and Co. Associated with group 3, however, are some sulphide-bearing portions, but they were not included in the material of the present study.

Ekojoki (20)

The Ekojoki intrusion is about 80 m long, up to c. 45 m wide, and narrows towards the southern end (Vesanto & Katajarinne 1984). Three lithological groups with grading modal composition were established on the basis of chemistry. They are lherzolites composed of olivine, orthopyroxene and clinopyroxene. The rocks of group 1 are the richest in olivine and sulphides.

Groups occur in drill intersections as continuous portions or with interfingering contacts.

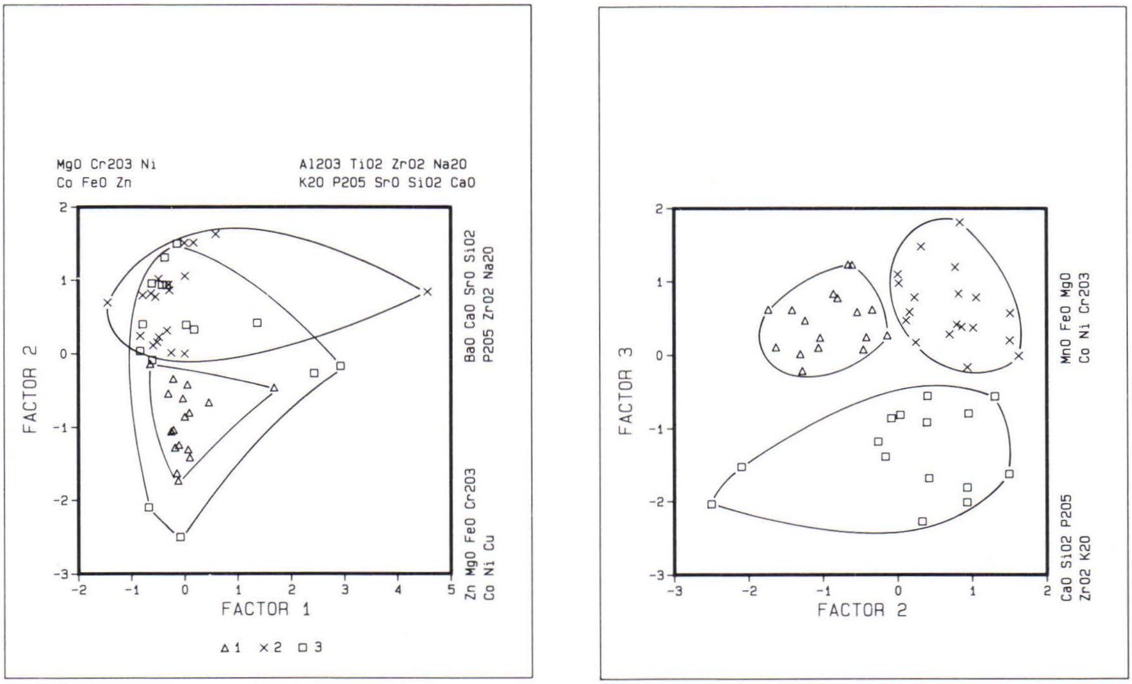

Fig. 8. Factor scores of the Posionlahti data. 1 and 2 = serpentinized dunites and lherzolites, 3 = lherzolites.

The rocks of group 1 are encountered mainly in the northern part of the intrusion and the rocks of group 3 in the margins and at the base of the intrusion.

The mode of occurrence and the high abundances of incompatible elements suggest that group 3 is contaminated. The magma of the Ekojoki intrusion already contained sulphides during its emplacement. The sulphides segregated rapidly from the magma, giving rise to sulphide and olivine cumulates of group 1 (Appendix 2). The segregation of sulphides was less prominent at the later differentiation stages.

Stormi (24)

The Stormi intrusion is composed of three superimposed lithological layers, from bottom to top: lherzolites, cortlandites and olivine websterites (Fig. 9) (Häkli & Vormisto 1985). On the ground surface the Stormi intrusion, with its maximum diameter exceeding 1 km, is the largest of the ultramafic targets (Papunen *et al.* 1979).

The samples of the present study were collected from the lowermost lherzolite layer and the middle cortlandite layer, mainly from the eastern part of the intrusion. Therefore, they are not very representative.

The rocks of the first three groups are lherzolites, and those of the fourth group are cortlandites. The cortlandites contain fine-grained or medium-grained amphibole, orthopyroxene and olivine. According to Häkli and Vormisto (op. cit.), the cortlandites exhibit signs of crystallization close to the surface. All the lherzolite groups are similar in mineralogy, with olivine, orthopyroxene and clinopyroxene as the essential minerals and chromite as an accessory. The proportions of the minerals vary so that the most mafic rocks are the richest in olivine.

Figure 10a shows all the lithological groups.

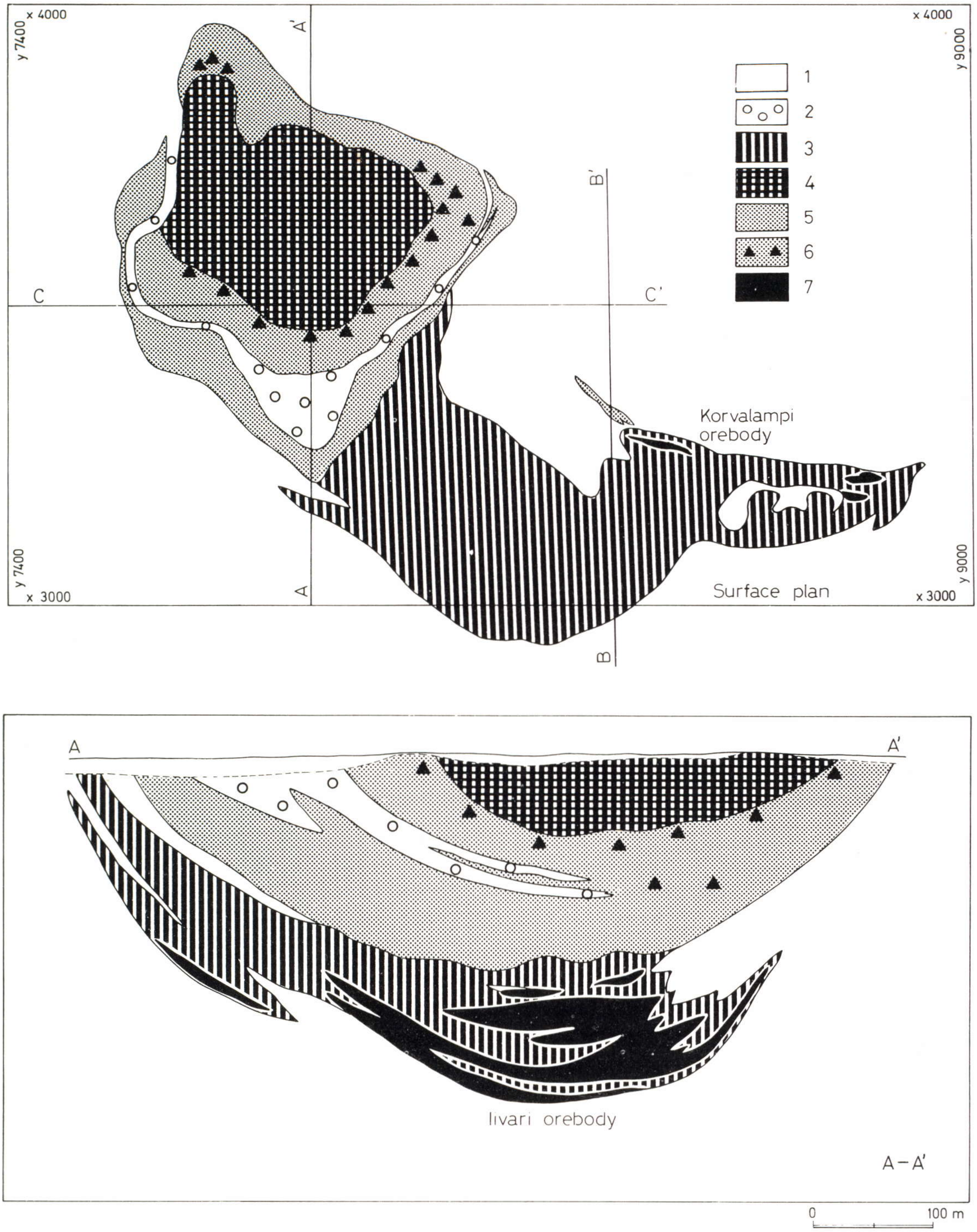

Fig. 9. Surface geology and cross-section of the Stormi intrusion after Häkli and Vormisto (1985). The quartz diorite that occurs together with the intrusion cuts the ultramafites and belongs to the extra-intrusional rock series. 1 = mica gneiss, 2 = quartz diorite, 3 = lherzolite, 4 = olivine websterite, 5 = cortlandite, 6 = agglomerate structure, 7 = ore.

The most conspicuous feature is the difference in composition between the cortlandites and lherzolites along factor 1. The difference in composition, which is clear despite the slight grading, is mainly due to the enrichment of the residual magma in incompatible elements, as shown by the fact that the loadings for these elements are the highest. The fractionation of mafic minerals and sulphides also took part in this event.

Figure 10b shows only the lherzolite groups. Their extensions along factors 1 and 3 are very similar. Factor 1 refers to the fractionation of olivine, because MgO and the incompatible elements have loadings with opposite signs. Factor 3 depicts the accumulation of olivine and orthopyroxene into the intercumulus material composed of clinopyroxene. Events proceeded in a similar manner in all the lherzolite groups, and they constitute a continuous compositional series along factor 2. The elemental combination of factor 2 suggests that the fractionation of sulphides was associated with the fractional crystallization of the silicate phase.

The most conspicuous culmination in the magmatic evolution at Stormi took place between the formation of lherzolites and cortlandites. The fact that the La/Yb ratio of the cortlandites is lower than that of the lherzolites indicates that the cortlandites derived from the lherzolites during the crystallization differentiation (Mäkinen 1984). The fractionation was intense as shown by the great distance between the rock types in Fig. 10a.

According to Huppert and Sparks (1984), fractional crystallization takes place in the margins of an intrusion. This is a local phenomenon capable of producing evolved differentiates that would normally require extensive fractional crystallization. The phenomenon is known as convective fractionation.

At Stormi the cortlandites may have derived from the residual magma accumulated by buoyancy and convection in the upper parts of the intrusion, where it formed layers varying in composition. According to Huppert and Sparks (op. cit.), segregated magmas are able to evolve as individual systems separated from each other by a sharp boundary. The fractionation of the magmas may also have facilitated the segregation of the sulphides. An alternative explanation for the mode of occurrence of the lherzolites and cortlandites is the discharge of magmas from a separate magma chamber. First a primary lherzolitic magma erupted, and after the fractionation of magma in the chamber the cortlanditic magma was injected cyclically. Thus the event would have been similar to that shown by the lithological assemblages at Ruth-Well (Nisbet & Chinner 1981).

If the amphibole of the cortlandites is primary (Mäkinen 1984), the partial water pressure in the cortlandite magma was high. Water entered the upper parts of the intrusion and altered the crystallization conditions of the cortlandite magma. The formation of two different layers in the Niqueland intrusion is attributed to a similar sequence of events (Girardi *et al.* 1986).

The lherzolites of groups 1 and 2 are located in the eastern part of the intrusion, close to the Korvalampi orebody. The rocks of group 3 occur south of it. The composition of the groups suggests that magma segregated into offshoots differing in sulphide content. At the same time the composition of the silicate phase changed as shown by the factor 2 loadings.

Haavisto (28)

The Haavisto intrusion is a discontinuous, narrow body, measuring c. 300 × 40 m, that grows still narrower westwards (Pehkonen 1984). It has three lithological groups (Appendix 2). Groups 1 and 2 consist of lherzolites, with olivine, orthopyroxene and clinopyroxene. Rocks of group 3 are olivine websterites with more clinopyroxene than the lherzolites.

Haavisto hosts some drill-indicated, high-grade sulphide occurrences, which means that the magma was already sulphide-saturated at the time of emplacement. The magma differentiated towards

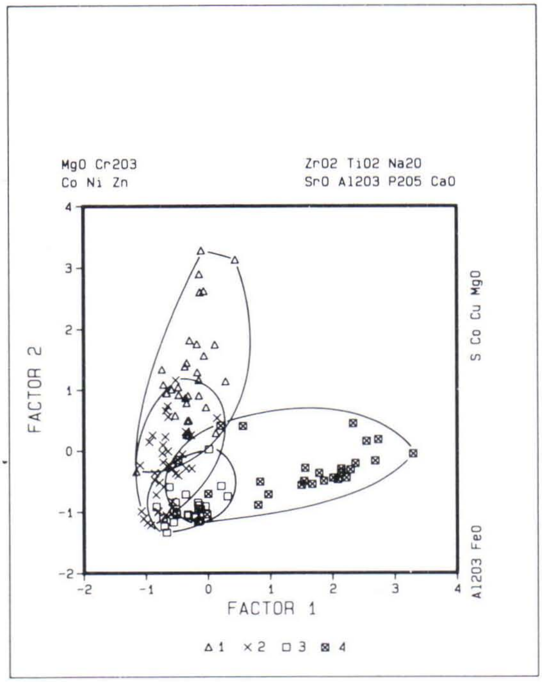

Fig. 10a. Factor scores of the Stormi data including both the lherzolitic and cortlanditic rocks. 1, 2 and 3 = lherzolites, 4 = cortlandites.

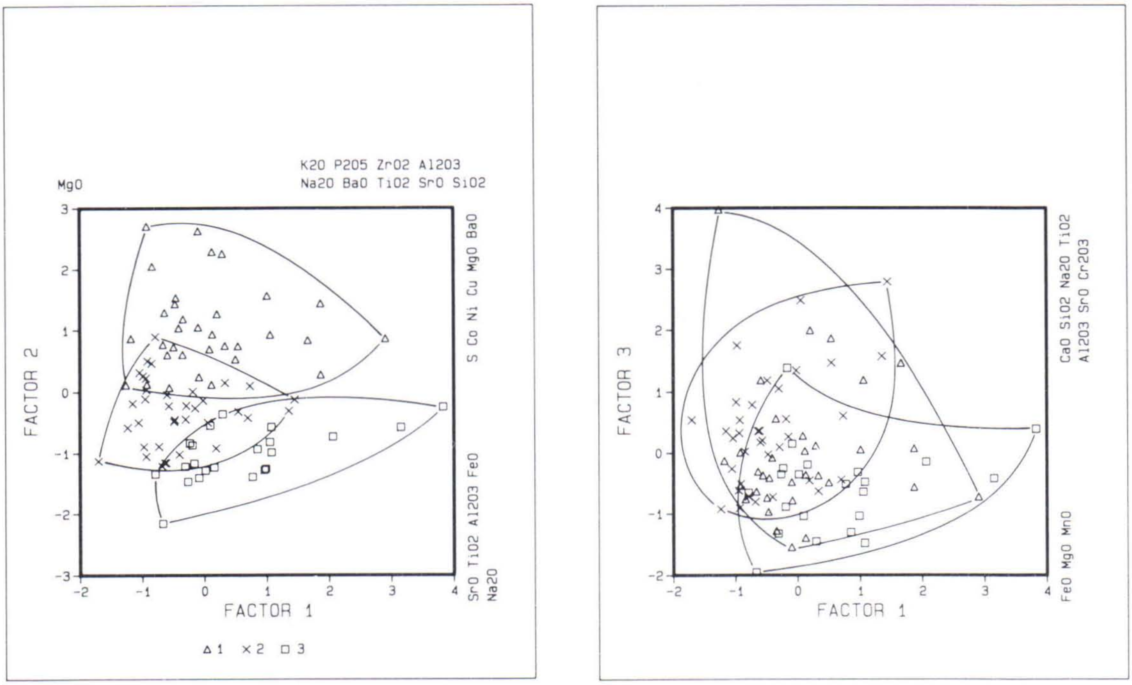

Fig. 10b. Factor scores of the Stormi data with the data on cortlandites deleted. The rocks are lherzolites. The abundances of sulphides and olivine decline from group 1 towards group 3.

the western part of the intrusion, for the proportion of group 3 increases westwards.

Suvitie (30)

The Suvitie intrusion measures about 200 × 400 m on the surface and extends to a depth of c. 300 m (Pehkonen 1983d). The intrusion is composed of three lithological groups. The rocks of group 1 are serpentinized lherzolites, and between groups 2 and 3 there is a continuous series of rocks from lherzolites to websterites. The websterites contain orthopyroxenes and clinopyroxenes. The petrological classification of the Suvitie rocks is somewhat defective, because the thin sections did not cover all the samples. Moreover, the marginal gabbros were not sampled.

The group 1 rocks occur at the base of the intrusion as a coherent layer overlain by the rocks of group 2. The proportion of group 3 increases upwards in the intrusion. According to the composition and mode of occurrence of the groups, the rocks of group 1 do not represent the same magma injection as the others (Appendix 2). Sulphides are encountered only at the base and in the margins of the intrusion, and their abundance is fairly low.

Kylmäkoski (32)

The Kylmäkoski intrusion is an elongated body with the most differentiated rocks located in the north (Fig. 11). The material was divided into three lithological groups on a geochemical basis. It was not possible, however, to connect the analytical data with the thin section data, and so, in the interpretation, use was made of the observations by Papunen (1980, 1985). Groups 1 and 2 are lherzolites with olivine, orthopyroxene and clinopyroxene. Group 2 is particularly rich in clinopyroxene. Group 3 is composed of websterites with orthopyroxene, clinopyroxene and minor olivine.

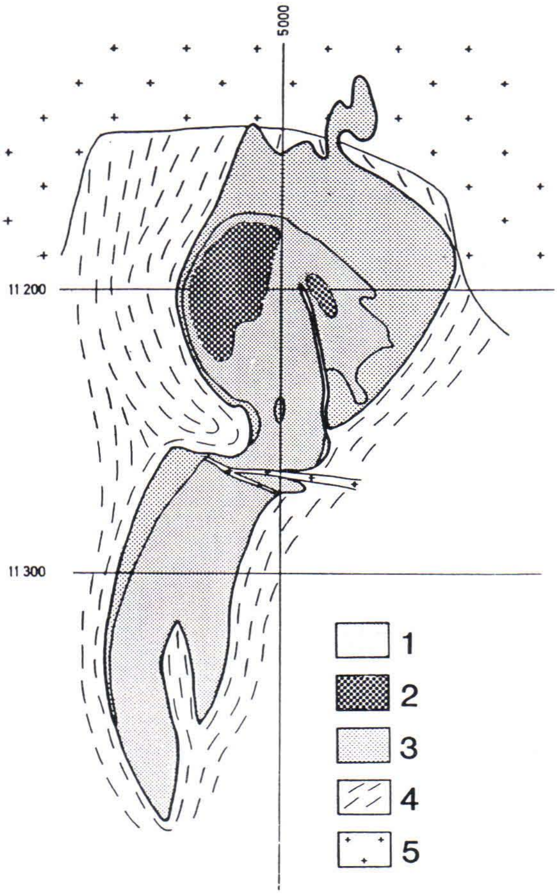

Fig. 11. Surface geology of the Kylmäkoski intrusion after Papunen (1985). 1 = lherzolite, 2 = orbicular lherzolite, 3 = websterite and hornblendite, 4 = mica gneiss, 5 = quartz diorite.

The crystallization of groups 1 and 2 proceeded in a very similar manner and there is no compositional gap between the groups (Fig. 12). However, group 2 exhibits lower factor 2 scores, which shows that the difference in composition is due to the accumulation of olivine and the enrichment of residual melt in the clinopyroxene. Factor 3 indicates that sulphides fractionated in both groups. The abundance gradient of P_2O_5 is the opposite to that of sulphides, but the loading for it is fairly low. The difference in composition between group 3 and the other groups along factor 1 is ascribed to the fractionation of olivine. Group 3 represents the most fractionated rocks at Kylmäkoski. Apart from three samples, the rocks of group 3 show only sparse sulphides.

In composition, group 1, group 2 and group

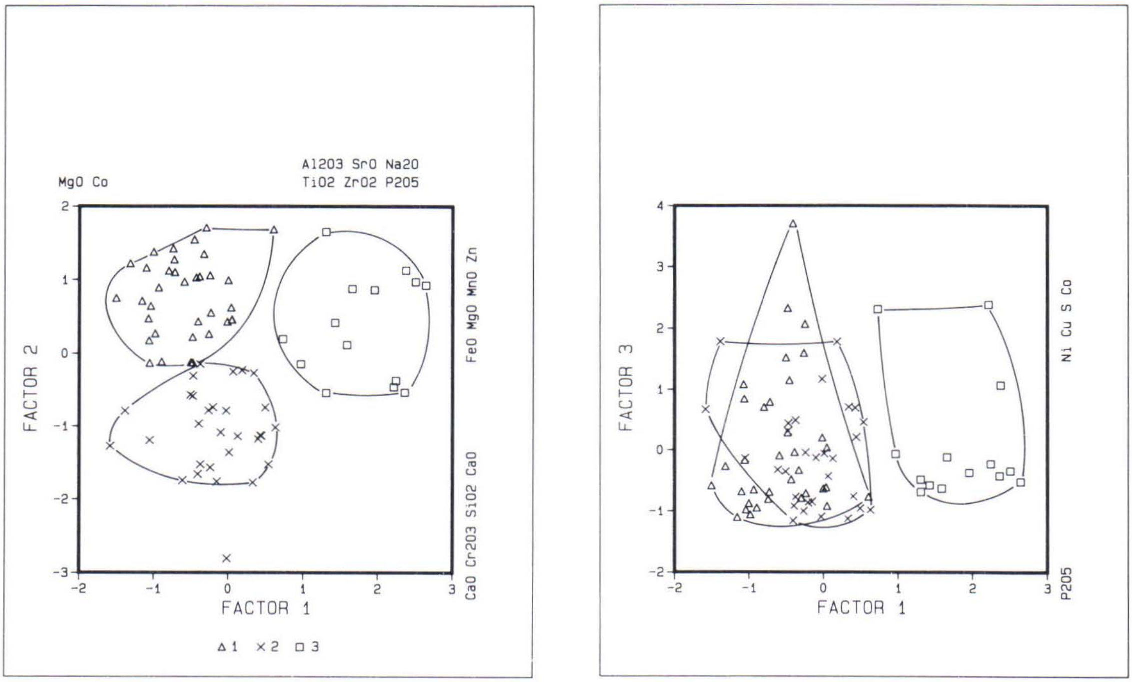

Fig. 12. Factor scores of the Kylmäkoski data. The lithological groups could not be correlated with the petrographic data. 1 and 2 are probably lherzolites, 3 = olivine websterites and websterites.

3 resemble the orbicular lherzolites (e.g. low Cr_2O_3), the lherzolites and the websterites, respectively, described by Papunen (1980, 1985) (Appendix 2). On account of the accumulation of olivine the residual magma probably became enriched in Cr_2O_3 when crystallization proceeded from group 1 to group 2 (cf. Arndt 1986). Crystallization proceeded towards the northern part of the intrusion, and the composition of magma changed more rapidly when the crystallization of websterites began. Abundant sulphides were formed during the crystallization of groups 1 and 2. The observations of Papunen (op. cit.) suggest that the magma was already sulphide-saturated at the time of injection. When websterites then crystallized segregation of sulphides almost ceased.

5. Gabbro intrusions in southern Finland

Large gabbro intrusions, of which the biggest has a diameter of 50 km, occur in the schist belt in southern Finland (Fig. 13). The intrusions consist mainly of gabbroic rocks that grade into hornblendites, diorites, quartz diorites and granodiorites. Associated with the Hyvinkää gabbro there are also small portions of lherzolite (Härme 1954).

The supracrustal rocks in the area include quartz-feldspar gneisses, mica gneisses, limestones and metavolcanics (Härme 1978, Neuvonen 1956).

The quartz-feldspar rocks and quartz-feldspar gneisses are predominantly arkosic sediments that grade into rhyolites or dacites. On account of metamorphism, however, the structures are not

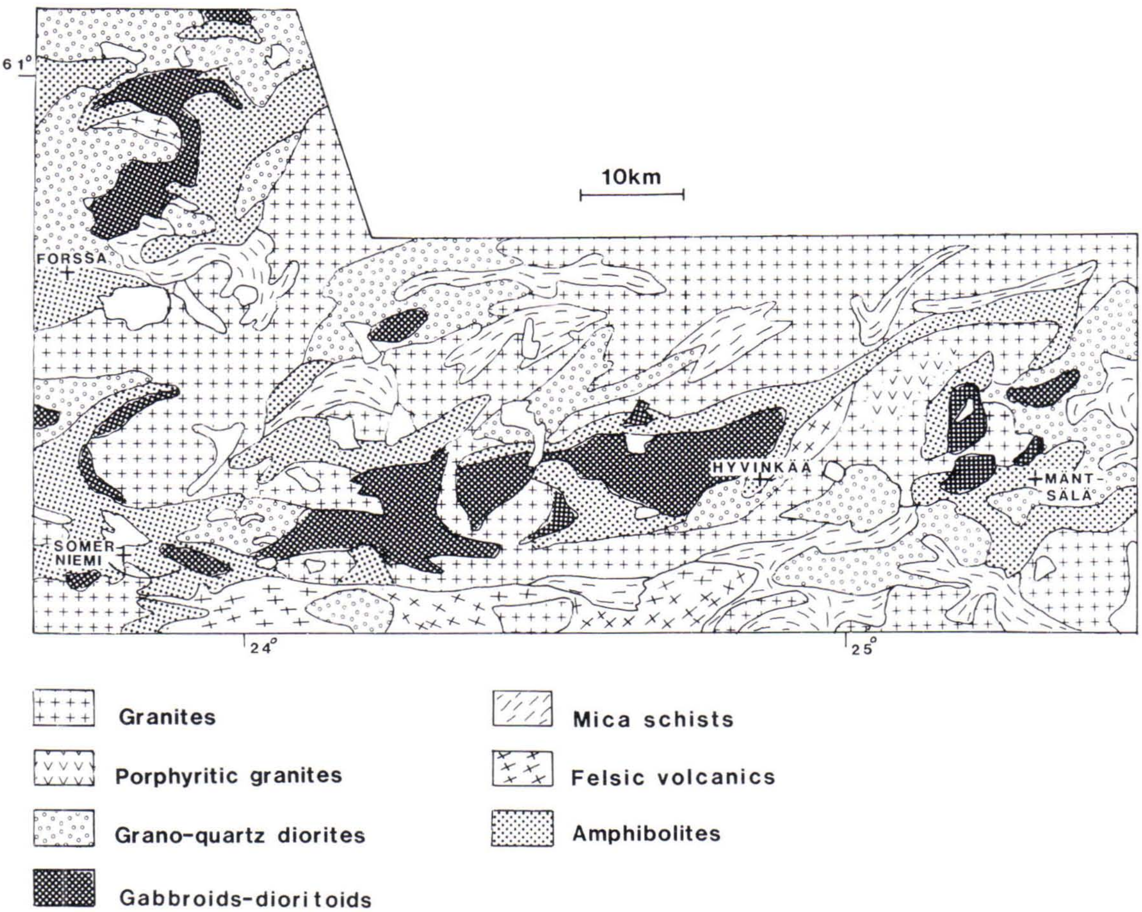

Fig. 13. Geological setting of the large gabbro intrusions in the schist belt of southern Finland and of their environment. Modified from the maps of Härme (1960, 1980).

readily recognizable. Associated with the quartz-feldspar gneisses there are calcitic limestones. Mica schists and mica gneisses are richer in quartz and biotite than are the quartz-feldspar gneisses. Layering is often well-developed and in places there are calcareous concretions. Micaceous rocks obviously deposited in deeper waters than did the quartz-feldspar rocks. Here and there there are garnetiferous and cordierite-bearing veined gneisses.

Mafic and intermediate volcanics are fairly common in the area. They exhibit flow, agglomerate and tuff structures and also uralite and plagioclase phenocrysts. The felsic volcanics that resemble quartz-feldspar rocks show porphyritic textures in places. The gabbro intrusions occur in association with the mafic volcanics, with which they are probably comagmatic.

Apart from mafic rocks, the predominant plutonic rock is microcline granite, which grades from a porphyritic to an aplitic variety.

Somerniemi (34)

The Somerniemi intrusion consists of three lithological groups. The rocks of groups 1 and 2 are amphibole gabbros with some pyroxenes. Petrologically they grade into the diorites and quartz diorites of group 3. On account of the small size of the material, information on the intrusion is fairly restricted.

Unpublished results of Häkli indicate that the rocks richest in nickel occur in the central parts of the intrusion. However, the intensity of the sulphide mineralization at Somerniemi was low (Appendix 2).

Forssa (36)

The Forssa intrusion consists of three lithological groups. The rocks of groups 1 and 2 are gabbros and diorites with amphiboles and pyroxenes, and the rocks of group 3 are diorites and quartz diorites. The boundaries between the groups are petrologically gradual. The number of samples, 75, is small in relation to the size of the intrusion.

The Forssa intrusion is irregular in shape. According to Häkli (1970), above-average Cu, Zn, Ni and S contents are met with only sporadically and they do not form a coherent sulphide occurrence. The average sulphide values are low (Appendix 2).

Hyvinkää (38)

The Hyvinkää intrusion, measuring 10 × 50 km^2, is the largest target of the present study. Since only 58 samples were taken, only the general outlines of the intrusion could be defined. The samples were divided into three lithological groups. Those of groups 1 and 2 are amphibolitized gabbronorites in which orthopyroxene predominates over clinopyroxene, and olivine is an occasional constituent. The rocks of group 3 are amphibole gabbros and diorites.

The sulphide-bearing rocks of group 1 occur in the central and eastern parts of the intrusion. The rocks of group 2 are distributed throughout the intrusion, whereas those of group 3 occur only in the west of the intrusion. The shape of the intrusion and the mode of occurrence of the groups suggest that the crystallization of magma proceeded westwards. Field observations of Hautala (1971) indicate that the sulphide mineralization was most intense in the gabbronorites in the northeastern part of the intrusion. Only four of the samples taken were comparable to those reported by Hautala, showing that the intensity of sulphide mineralization was low (Appendix 2).

Mäntsälä (40)

The Mäntsälä material derives from four massifs located close to each other. It constitutes two lithological groups composed of amphibole gabbros and diorites with some minor pyroxenes.

The present material amounts to only about 30 % of the Mäntsälä material studied by Huhma (1978). Despite some significant differences, the factor loadings of both studies are rather similar. The present study did not reveal the bimodality in Fe values reported by Huhma from his material.

The differences between the groups are mainly due to the concentrations of incompatible elements (Appendix 2). The high BaO, K_2O and P_2O_5 values in group 2 are ascribed to contamination, because there is no difference in the transition element concentrations between the groups.

6. Ahokkala environment

The Ahokkala intrusion is embedded in supracrustal mica gneisses close to the contact of a rapakivi massif. The mica gneisses are often veined, and metamorphism has obliterated the primary features. Zones of massive amphibolites with calcareous interlayers are associated with the mica gneisses, and narrow amphibolite horizons occur at the edges of the intrusion. Plagioclase porphyritic metabasalts are met with in the vicinity.

Porphyritic granodiorite and quartz diorite occur south of the Ahokkala intrusion, and to the northwest there are large gabbro-diorite massifs that, according to Vorma (1965), exhibit hypabyssal features.

Ahokkala (42)

The Ahokkala intrusion consists of two lithological types: gabbros and diorites containing pyroxenes and amphiboles. Norites are also encountered. There is no distinct petrological boundary between the groups, although group 1 is richer in mafic minerals than group 2. On account of the small number of samples the picture of the intrusion is only tentative.

The norite at Ahokkala contains small nests of sulphides. The S, Cu and Co contents in the groups of the present study are almost identical. However, the Ni content is twice as high in the more mafic group 1 as in group 2 (Appendix 2).

7. Parikkala environment

There is only one intrusion in the Parikkala area with a differentiation series ranging from olivine websterites to hornblendites and gabbros. The olivine websterites are the richest in sulphides, although no sizable occurrences have been encountered in them.

The supracrustal rocks in the Parikkala area are mainly kinzigites that grade into fine-grained pelites and mica gneisses. The pelites contain black schists, tuffites and quartz-feldspar gneisses as interlayers. The schist formation has diopside amphibolites with the associated limestones and quartzites in its basal parts (Nykänen 1983).

The plutonic rocks vary in composition between synorogenic potassium feldspar granites, oligoclase granites and late-orogenic potassium feldspar granites. Charnockitic granodiorites occur together with kinzigites.

Parikkala (44)

The Parikkala gabbro intrusion is composed of three zones produced by differentiation. Hornblende gabbros occur in the northern part of the intrusion, pyroxene gabbros in the middle, and olivine gabbros and olivine websterites in the south. The marginal parts of the intrusion contain schist and granodiorite fragments, which have caused some contamination in the mafic magma. Northwest of the intrusion there is a granite with pegmatoids and aplites (Nykänen 1983).

On geochemical grounds the Parikkala material was divided into two lithological groups: amphibole gabbros and norites, both of which contain varying abundances of orthopyroxene, clinopyroxene, plagioclase and amphibole (Fig. 14). According to Papunen (1962), the boundary between the pyroxene-bearing and amphibole-bearing rocks is gradual. In places, group 1 contains olivine and is richer in orthopyroxene than group 2. The olivine websterites were not included in the present material.

On account of the small number of samples the groups are scattered in the factor diagrams (Fig. 23). They differ from each other only along factor 1, which refers to the fractionation of mafic minerals and plagioclase. Factor 2 represents the fractionation between plagioclase and residual magma. According to this, the fractionation in group 2 was somewhat more advanced than that in group 1. Factor 3 refers to the crystallization of Fe-Ti oxides, due to which the abundance of FeO declines relative to that of SiO_2 (Kushiro 1979). This, too, suggest that the fractionation advanced further in group 2 than in group 1. Cr_2O_3 is incorporated in the silicate phase, because the sign of the loadings for

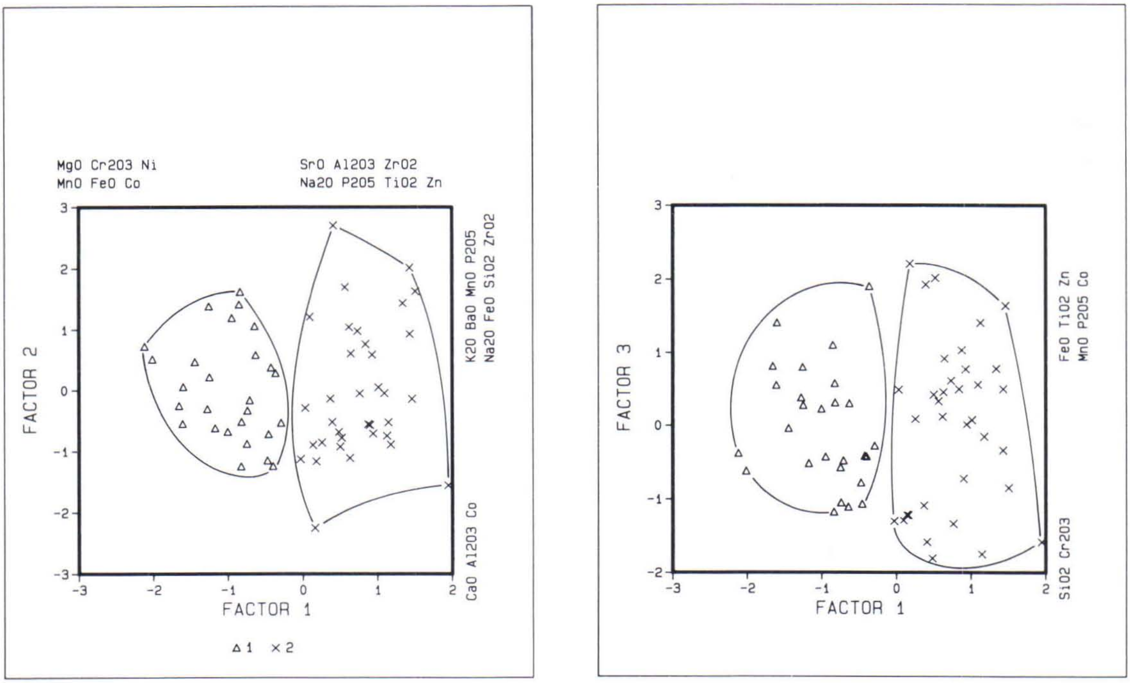

Fig. 14. Factor scores of the Parikkala data. 1 = norites, 2 = gabbronorite. The petrographic boundary between the groups is gradual.

Cr_2O_3 is the opposite of those for FeO and TiO_2.

Huhma (1978) reports a compositional minimum for MgO at 9 % in his Parikkala material. Group 1 corresponds to the rocks that contain less than 9 % MgO, and group 2 to the rocks containing more than 9 % MgO. The material of Huhma was bigger than that available for the present study. The loadings on the factors in both studies are almost identical, which means that despite the difference in size the materials represent the same rocks. According to the mean compositions, group 1 is more primitive than group 2, because the abundances of Cr_2O_3 and Ni are higher and those of incompatible elements lower than in group 2 (Appendix 2). However, there is no marked difference in the abundances of Cu, Co and S in the groups. This is in accordance with the results of Häkli (1970), who showed that the Cu-S factor scores have a fairly even distribution over the intrusion, unlike the Ni factor scores, which cluster in the southern part of the intrusion where the rocks of group 1 occur. All rock types are thus sulphide-bearing but group 1 is the richest in Ni.

8. Haukivesi environment

There are numerous mafic and ultramafic intrusions in the environment of the lake Haukivesi, and five of them were included in the present study (Fig. 15). The Laukunkangas intrusion, which is economically the most important, hosts 4.5 M.t. of nickel ore assaying 0.33 % Ni and

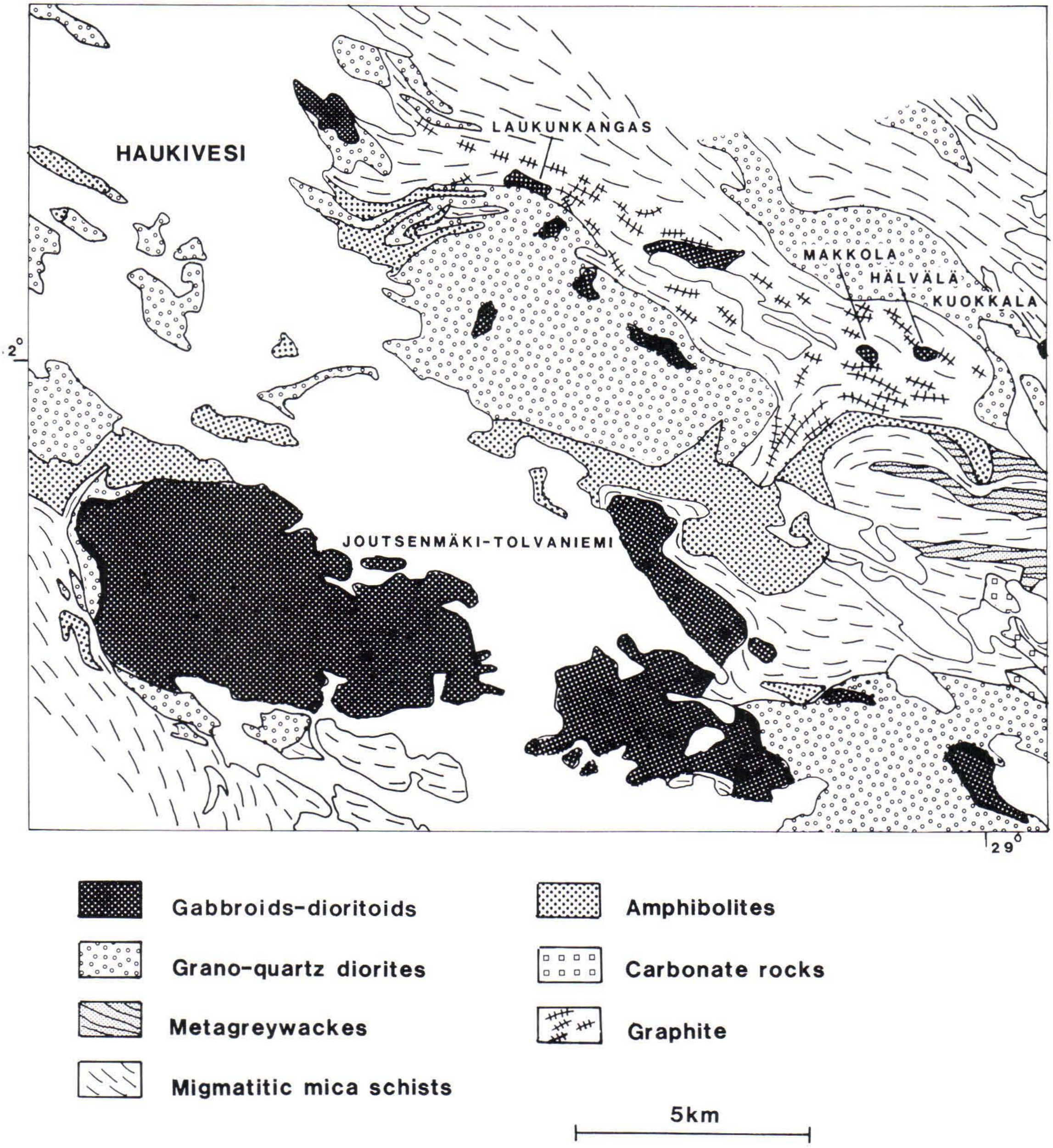

Fig. 15. Geology of the Haukivesi environment. Modified from the map of Grundström (1980).

0.1 % Cu (Grundström 1980). The sulphides occur at the base of the intrusion or as offsets. The Hälvälä intrusion also contains a subeconomic offset occurrence. The rocks in the intrusions grade from lherzolites into norites and gabbros. The Joutsenmäki-Tolvaniemi intrusion differs from the other Haukivesi intrusions, because it ranges from gabbros to quartz diorites and is the largest intrusion in the area.

The supracrustal rocks of Haukivesi have been

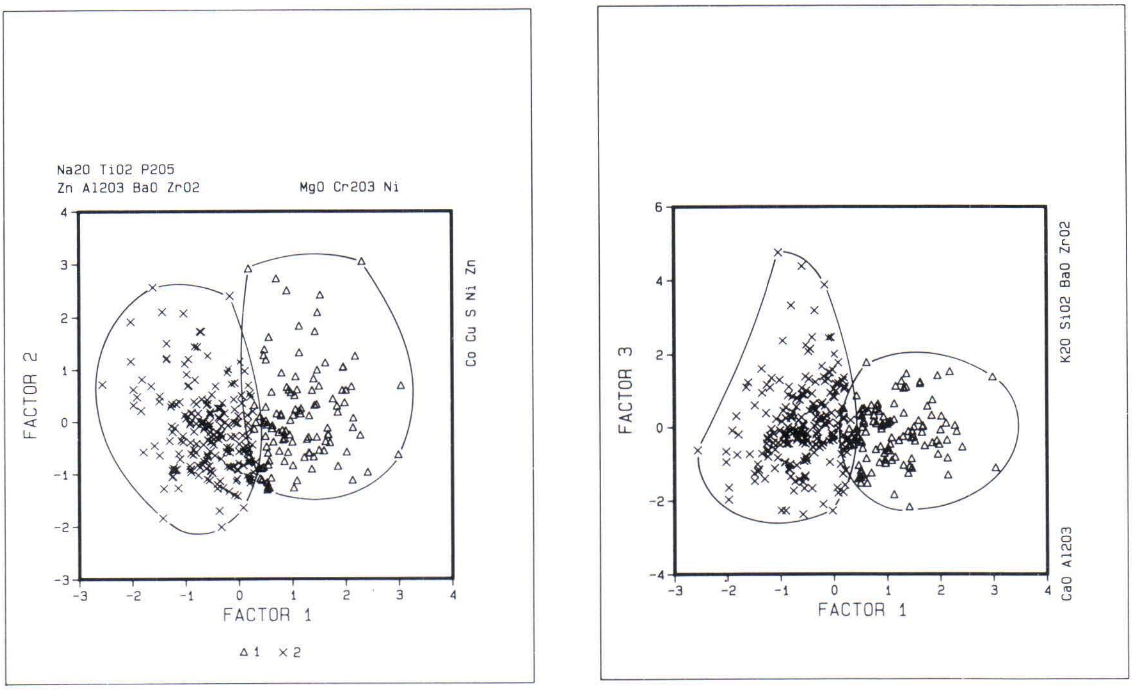

Fig. 16. Factor scores of the Joutsenmäki-Tolvaniemi data. 1 = gabbros and diorites, 2 = diorites and quartz diorites. The groups constitute a gapless petrological series.

divided into two groups: volcanics and sedimentary rocks. The massive diopside amphibolites that abound in the area are included in the volcanics. The sedimentary rocks are metagreywackes and calcium-bearing metasediments. The metasediments constitute an eugeosynclinal assemblage that occurs farther north, and a miogeosynclinal assemblage that is located farther south.

The intruding plutonic rocks formed migmatites with the supracrustal rocks. Typical plutonic rocks of the area are trondhjemites, although in composition the plutonic rocks vary from quartz diorites to ultramafites. According to Gaál and Rauhamäki (1971), charnockites are also associated with the ultramafics.

The deformation style of the migmatites is similar to that encountered in the Vammala area (Koistinen, pers. comm.). Multiphase folding has produced breccia migmatites, schollenmigmatites and boudinages.

Joutsenmäki-Tolvaniemi (46)

The Joutsenmäki-Tolvaniemi intrusion, measuring 5 × 20 km, is the second biggest target of the present study. The 335 samples taken constitute a fairly representative population. The intrusion was originally a lopolith, in which gabbros and diorites occurred concentrically (Parkkinen 1975). Deformation has obliterated the primary structures. According to Parkkinen, the primary contacts between the gabbros and diorites were gradual, although in places magmatic crosscutting is also encountered.

The intrusion is composed of gabbros, diorites and quartz diorites that grade gaplessly into one other. Plagioclase is the most common essential mineral and orthopyroxene predominates over clinopyroxene. The most mafic gabbros contain olivine.

As shown by Fig. 16 the material constitutes a gapless compositional series. The artificial boundary between the groups is perpendicular to factor 1, which represents the fractionation of orthopyroxene and the enrichment of the residual magma in incompatible elements. The rocks of group 1 have high factor 1 scores because they are gabbros. The groups plot within the same area along factor 2, which refers to the fractionation of sulphides. Factor 3 represents the fractionation of plagioclase and residual melt. The rocks of group 2 grade into fairly silicic variants, for they have the highest factor 3 scores.

According to Häkli (1971), the Joutsenmäki-Tolvaniemi intrusion was emplaced in two stages. In composition, group 1 is more primitive than group 2, since it contains more Cr_2O_3 and Ni (Appendix 2). The rock types, however, constitute a gapless series along factor 1, showing that the magma types of the intrusion are very closely related to each other.

Kuokkala (48)

The samples of Kuokkala were taken from two intrusions about 400 m apart. One of them is platy in shape and the other roundish; only seven samples are from the platy massif. The intrusions, which are conformably embedded in mica gneisses (Eeronheimo 1984), are composed of amphibole-bearing gabbros with plagioclase as a cumulus phase. The drill intersections do not show any marked sulphide mineralizations (Appendix 2).

Hälvälä (50)

The Hälvälä intrusion is a cup-like body surrounded by satellite formations. The coherent part of the intrusion is c. 70 m in diameter and extends to a depth of c. 100 m. On the basis of geophysical results, Eeronheimo (1985a) proposed that the Hälvälä intrusion is connected with the Makkola intrusion 1 km away.

The Hälvälä intrusion is composed of three lithological groups. The rocks of group 1 are mainly norite with euhedral orthopyroxene crystals and anhedral plagioclase. The rocks of group 2 resemble the norites of group 1 but are richer in plagioclase. These plagioclase-rich rocks grade into the leuconorites of group 3, in which plagioclase occurs as subhedral crystals. All the groups contain random clinopyroxene.

According to drill intersections, groups 1 and 2 occur as continuous portions in the cup-like main massif, whereas the rocks of group 3 are located mainly in the satellite massifs. The segregation of the sulphides was the most important event in the Hälvälä intrusion, and it is to this that the difference between groups 1 and 2 can be ascribed. The formation of the massive offset orebody is probably due to deformation.

Normal crystallization differentiation could not have produced the rocks of group 3 from those of groups 1 and 2, because the abundances of TiO_2, BaO, K_2O and P_2O_5 in group 3 are too low (Appendix 2). All the lithological groups contain sulphides and thus obviously belong to the same differentiation series. The crystallization conditions of group 3 may have differed from those of groups 1 and 2, as suggested by the fact that the rocks of group 3 are located far from the main massif. The abnormal magmatic evolution is ascribed to fragmentation of the intrusion, due to which the magma was able to evolve in different ways under different physical conditions.

Makkola (52)

The ground surface section of the Makkola intrusion measures c. 300 × 800 m but its depth is unknown (Eeronheimo 1985b). The intrusion is composed of five lithological groups, of which the first four are homogeneous norites composed of orthopyroxene and plagioclase. Not only the modal compositions but also the chemical compositions of the norites are fairly similar (Appendix 2). Group 5 contains gabbros with plagioclase, pyroxenes and amphibole. Here and there in the Makkola intrusion there are also lher-

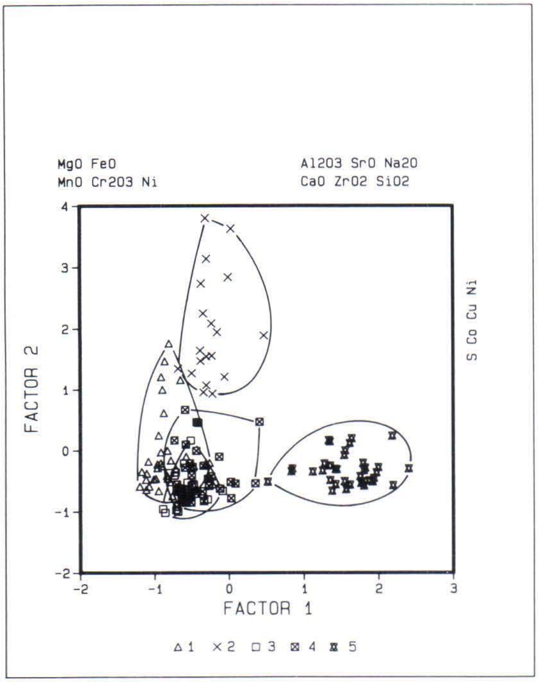

Fig. 17. Factor scores of the Makkola data. 1, 2, 3 and 4 are melanorites, 5 = gabbronorites.

zolites, but owing to the small number of samples they were not included in the present study.

Figure 17 shows all five groups. Group 5 differs most clearly from the other rock types along factor 1, which represents the relative abundances of plagioclase and mafic minerals.

The drill sections show that the rocks of groups 1 and 2 are associated with group 4 as separate occurrences. Groups 1 and 5 also alternate, although group 5 occurs as long continuous portions, too. The groups differ from each other too much, however, to be members of one and same crystallization series. The relationships between the rock types suggest that the Makkola intrusion was formed from two magma injections. It is not possible to establish the age relations of the injections from the information available. However, groups 1, 2, 3 and 4 are ascribed to the bigger magma injection and group 5 to the smaller one. Crystallization was very regular, except that some sulphides were segregated when group 2 crystallized (Appendix 2).

Laukunkangas (55)

The Laukunkangas intrusion is an oval body trending east-west, with a major diameter of c. 950 m. The bulk of the intrusion is composed of norites, although there are also some ultramafics in the east (Fig. 18). Since the material of the present study derives from the rocks in the eastern part, more emphasis is given to the ultramafics.

The rocks in the intrusion were divided into five groups on a geochemical basis. The groups were not classified petrologically because it was impossible to correlate the XRF data with the thin section data. The analytical data, however, were correlated with the petrological observations of Grundström (1980, 1985) and Sutinen (1985). According to the mean compositions, the rocks of groups 1 and 2 are lherzolites, olivine norites and olivine gabbros; group 3 comprises sulphide-bearing norites; group 4 sulphide-free norites and group 5 cummingtonite gabbros and melagabbros (Appendix 2). There is also a smaller data set for the Laukunkangas intrusion, in which the AAS and XRF analytical data were pooled. This material, too, was submitted to factor analysis, and the factors resolved are included in Appendix 1. The distribution of data is similar in both factor diagrams.

The most conspicuous feature in the Laukunkangas intrusion is the clustering of the samples into two large groups along factor 2, i.e. into sulphide-bearing and sulphide-free groups (Fig. 19). The sulphide-free rocks cluster in the lower part of Fig. 19, whereas the sulphide-bearing ones plot as a more scattered group in the upper part of the figure. There is a weak compositional minimum between the sulphide-free and sulphide-bearing rocks. As suggested by factor 2, the fractionations of sulphides and plagioclase were opposite events.

The rocks of group 4 show the narrowest clus-

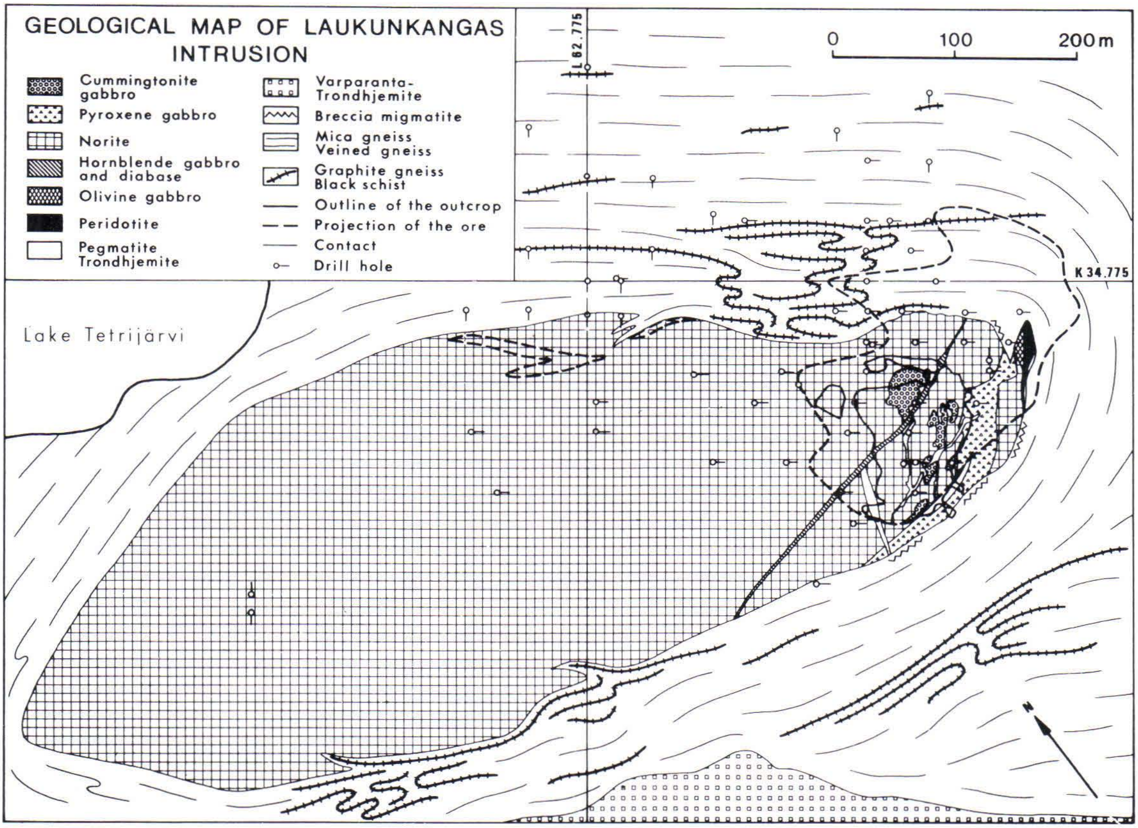

Fig. 18. Surface geology of the Laukunkangas intrusion after Grundström (1985).

tering in Fig. 19. They contain abundant plagioclase, for factor 1 represents the fractionation between plagioclase and orthopyroxene. The silicate portions of groups 3 and 4 correspond to each other, because their mean compositions are almost equal and they are distributed in the same area along factor 1; the groups differ only in sulphide content. Another cluster is due to the rocks of group 2, which are richer in mafic minerals than those of group 4. Group 5 differs from the other rocks along factor 3, which most probably refers to contamination.

Grundström and Sutinen (op. cit.) divided the rocks at Laukunkangas into two main groups: those containing sulphides and those free of sulphides. On the basis of normative compositions, Grundström (1980) postulates that magma was injected in two stages: first sulphide-bearing lherzolites and norites and then sulphide-free norites and gabbros. According to this model, groups 1, 3 and perhaps 2 would belong to the first injection phase and groups 4 and 5 to the second one.

Excluding the contents of Cu, Ni, Zn and S, the mean compositions of groups 3 and 4 are almost identical. The distribution of the groups along factor 1 is also similar. The relationship between the rocks of groups 1 and 2 is much the same. Therefore, it is likely that groups 1 and 2 are associated with the first injection phase and groups 3 and 4 with the second one. This is not compatible with the order of injection proposed by Grundström. The discrepancy might be due to the FeO contents. Grundström used total iron, whereas in the present study the iron incorporated in sulphides was subtracted from the total iron.

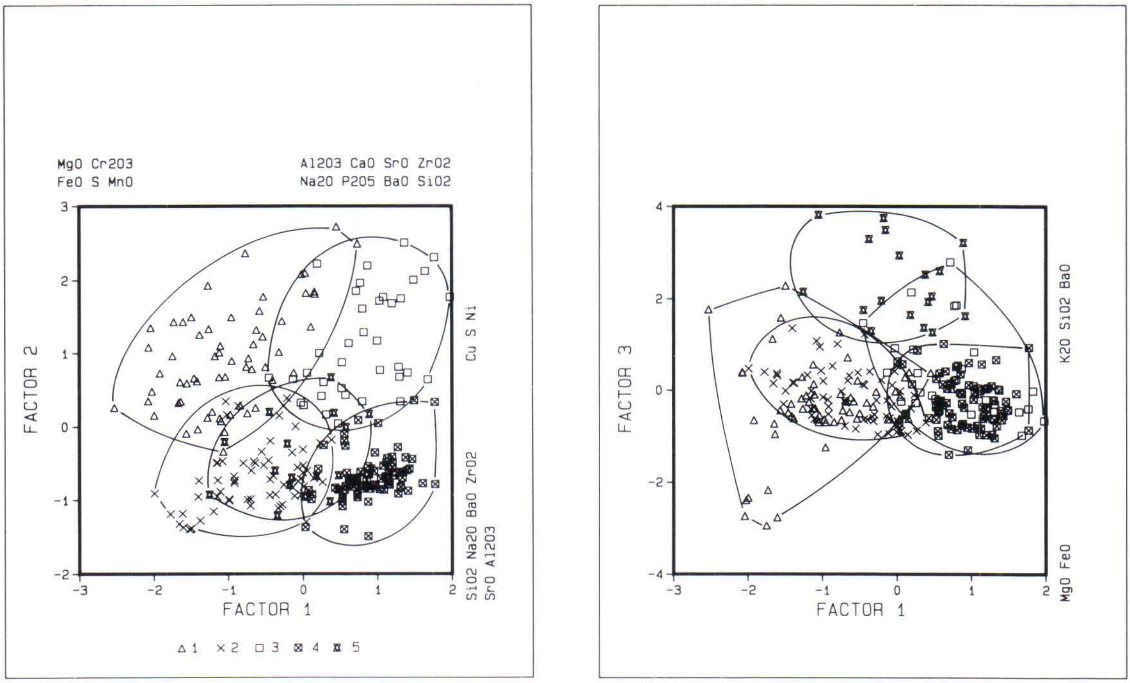

Fig. 19. Factor scores of the Laukunkangas data. The lithological groups could not be correlated with the petrographic data. 1 = lherzolites and olivine norites rich in sulphides, 2 = lherzolites and olivine norites poor in sulphides, 3 = norites rich in sulphides, 4 = norites poor in sulphides, 5 = cummingtonite gabbros.

The order of injection of the magma types can also be approached with the aid of lithological associations. In the drill intersections, groups 1 and 2 often alternate, as do groups 3 and 4. The lithological associations, however, show considerable overlap. From them it can be deduced that groups 1 and 2 belong to the first magma injection and groups 3 and 4 to the second one. Group 5 is associated with the second magma injection, because it often occurs as interlayers in the rocks of group 4. The rocks of group 5 represent hybrid rocks of group 4, as suggested by their random mode of occurrence and high SiO_2 and K_2O values.

The weak concentration minimum between the sulphide-bearing and sulphide-free rocks along factor 2 indicates that the segregation of sulphides was efficient in both magma injections. On the basis of the mean concentrations and the number of samples the first magma injection was richer in sulphides than the second one. The injected magmas were obviously already sulphur-saturated at the injection stage. According to factor 2, sulphides also segregated during fractional crystallization, when the rocks of groups 1 and 2 were formed. As shown by the compositional minimum between the groups along factor 2, however, the sulphides were not segregated from the norites during the fractional crystallization but immediately after injection, and the sulphide-bearing norites (group 3) and sulphide-free norites (group 4) crystallized from the same parent magma.

The low sulphide content of norites at the crystallization stage might possibly be ascribed to the cumulative crystallization of plagioclase. According to Mathez (1976), the crystallization of plagioclase shifts the composition away from the sulphur-saturated field, when FeO increases in the residual magma.

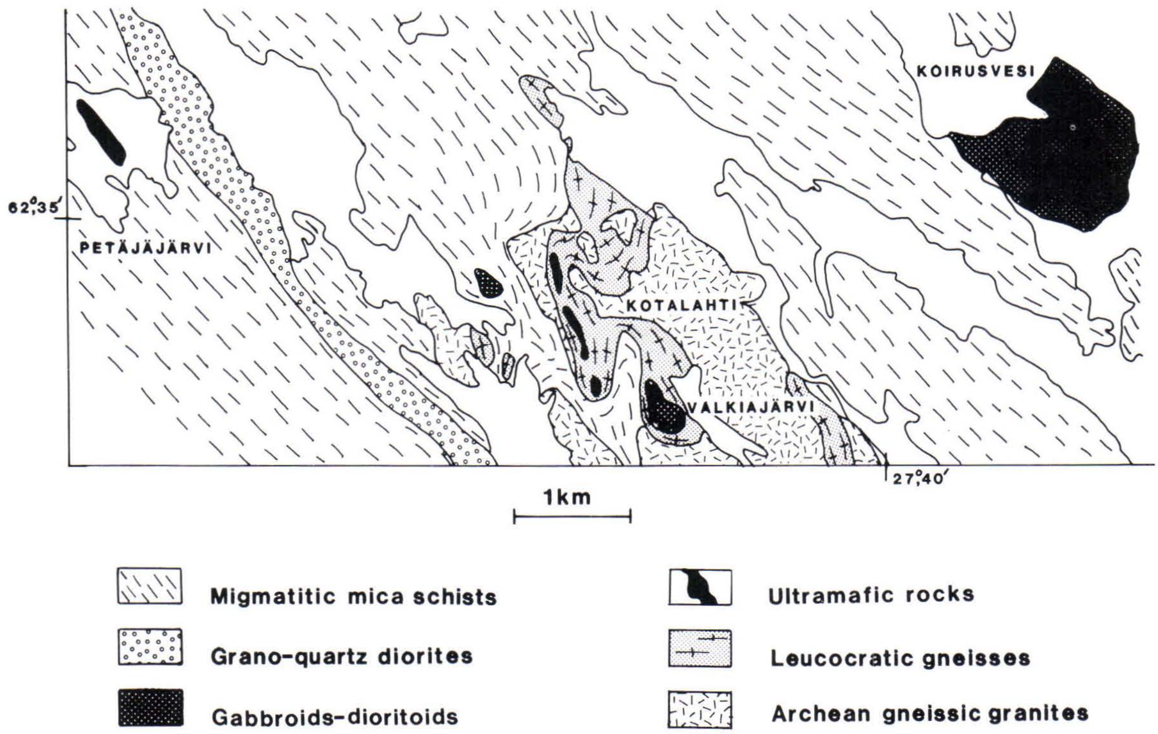

Fig. 20. Geology of the Kotalahti area modified from the maps of Gaál (1980) and Outokumpu Oy.

9. Kotalahti environment

Several intrusions containing peridotites, pyroxenites, norites and gabbros occur in the environment of Kotalahti. Economically most important is the Kotalahti intrusion, for it hosts about 10 M.t. of ore grading 0.7 % Ni and 0.27 % Cu (Papunen and Koskinen 1985); the other intrusions are only slightly mineralized. The Kotkatsuo intrusion is located in the least interesting area in terms of ore potential, as it lacks sizable schist occurrences. The intrusions are located in the Savo schist belt and are embedded in migmatites and gneisses that derived from pelitic and psammitic sediments (Fig. 20). There are also volcanic diopside amphibolites. In places, fragments of Archaean basement have risen into dome structures rimmed by schists (Gaál 1980).

The plutonic rocks vary in composition from quartz diorites to ultramafics and crosscut the basement gneisses but not the mica gneisses. Synkinematic and late-kinematic intrusive rocks with ultramafic hornblendite portions were emplaced after the mafic and ultramafic intrusions.

At least five deformation phases can be identified in the Kotalahti area. The intrusions containing mafic and ultramafic rocks were emplaced during the third deformation phase (Gaál op.cit.).

Valkiajärvi (56)

The Valkiajärvi intrusion, which is an oval body in shape (Fig. 20), has three lithological groups. Group 1 is composed of gabbronorites with orthopyroxene and clinopyroxene. Orthopyroxene predominates over clinopyroxene, and plagioclase occurs as large poikilitic crystals either

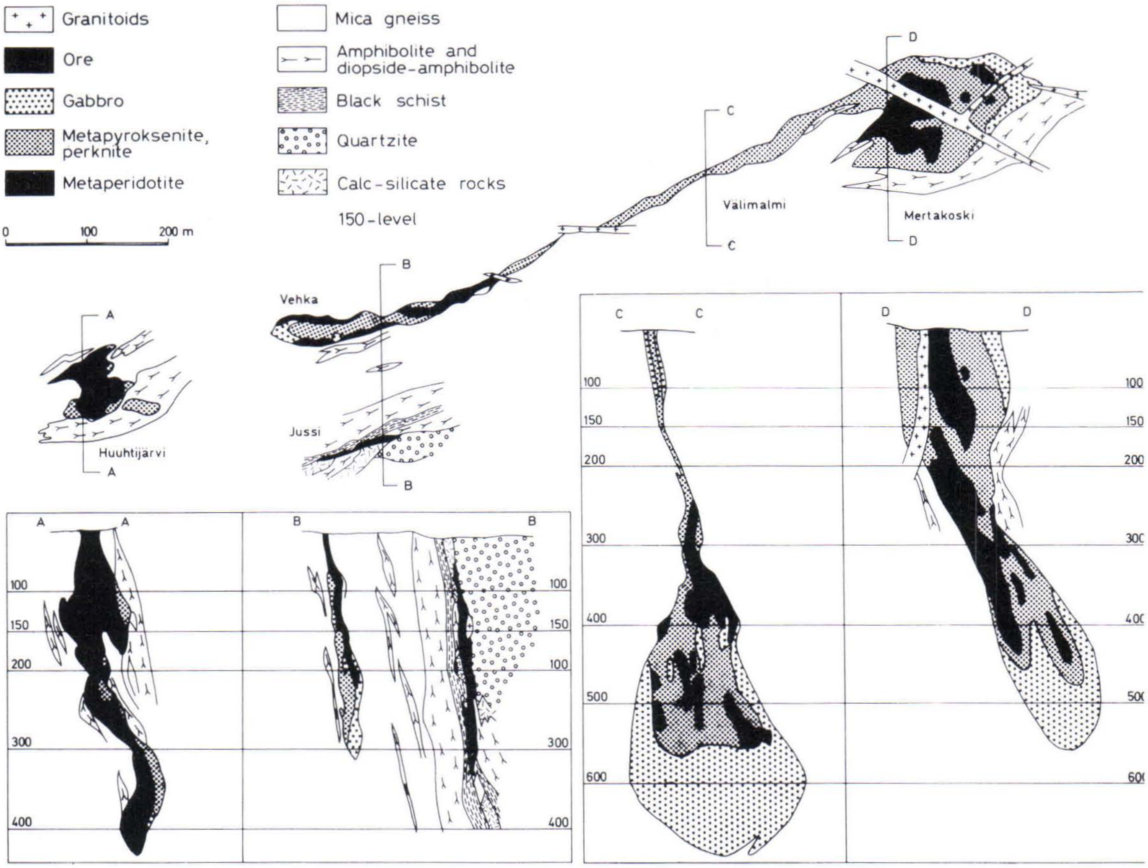

Fig. 21. Surface geology and cross-sections of the Kotalahti intrusion after Papunen and Koskinen (1985).

as intercumulus crystals or, occasionally, as euhedral ones. The rocks of group 2 are also gabbronorites but clinopyroxene predominates over orthopyroxene, and plagioclase occurs as euhedral crystals. Group 3 consists of leucogabbros with orthopyroxene and clinopyroxene. The plagioclase crystals are euhedral. All the rocks are metamorphosed to some extent. The Valkiajärvi gabbro is heterogeneous in composition, as shown by the 16 % of outliers deleted from the material on the basis of their great Mahalanobis distance from the data mean, probably due to the small number of samples relative to the size of the intrusion.

The bulk of the rocks at Valkiajärvi belongs to group 2, which occurs as continuous portions in drill intersections. In places, group 1 rocks are met with as interlayers in group 2 rocks, although long drill intersections have also been recorded for group 1. The rocks of group 3 occur here and there in the margins of the intrusion.

Gaál (1980) divided the rocks of Valkiajärvi into two groups: 1) uralite gabbros and pyroxene gabbros, and 2) hornblende gabbros. The cross-cutting relations show that the uralite gabbros and pyroxene gabbros were intruded first followed by the hornblende gabbros. On the basis of petrographic and geochemical data, group 1 has been correlated with the uralite gabbros and pyroxene gabbros of Gaál. Groups 2 and 3 can-

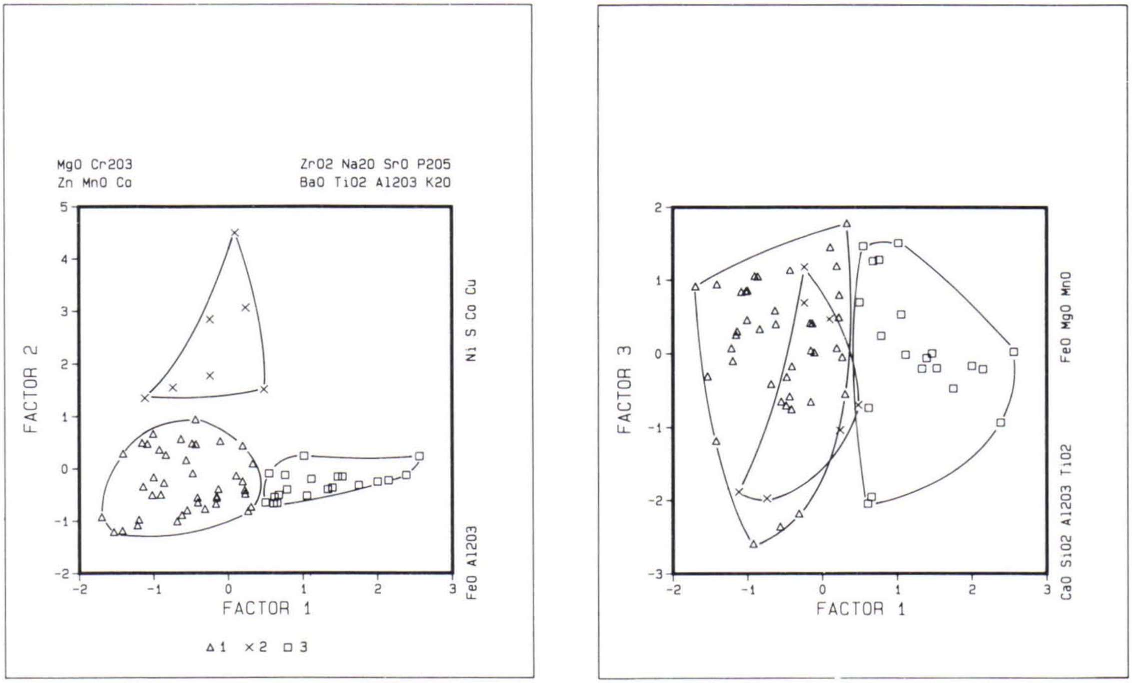

Fig. 22. Factor scores of the Kotalahti data. 1 = lherzolites poor in sulphides, 2 = lherzolites rich in sulphides, 3 = websterites.

not be related petrographically to amphibole gabbros although in composition they exhibit similarities.

Group 3 differs from the other Valkiajärvi groups. Its SiO_2 and Na_2O values are high and those of CaO and incompatible elements low (Appendix 2). Normal fractional crystallization could not lead to a lithological composition of group 3 from the compositions of groups 1 and 2. Hence group 3 represents either a different magma injection or hybrid rocks. The latter is the more likely, as suggested by the scattered mode of occurrence of group 3.

Kotalahti (58)

The Kotalahti intrusion is a 1 km long platy and rather dismembered body (Fig. 21). The material of the present study is limited, because it is composed mainly of ultramafic rocks and does not include any gabbos (cf. Papunen and Koskinen 1985). Moreover, it was not possible to locate the sampling sites of the specimens accurately. However, with the aid of the studies of Huhtala (1969), the groups were placed approximately in their correct sites in the intrusion.

The material was divided into three lithological groups. The rocks of groups 1 and 2 do not differ petrologically, being lherzolites composed of olivine, orthopyroxene and clinopyroxene. In places plagioclase occurs as an intercumulus mineral. The rocks of group 3 are websterites with orthopyroxene and less abundant clinopyroxene. Occasionally they also contain olivine or plagioclase.

Group 2 has only a few samples, but they all are rich in sulphides (Fig. 22). The boundary between groups 1 and 3 is defined by factor 1, although there is no compositional gap between the groups. Factor 1 refers to the fractionation of Fe-Mg minerals as a result of which magma became depleted in FeO, MgO, MnO and Cr_2O_3

and enriched in incompatible elements. Factor 3 represents the relative abundances of mafic minerals and plagioclase.

According to Huhtala (op. cit.), lherzolites occur in the platy upper part of the intrusion and in the middle of the spherical basal part. The contour lines on the maps depicting the distribution of element concentrations follow the lithological zones. The rocks richest in incompatible elements are located in the margins of the intrusion and probably represent the rocks of group 3, which have high scores of factor 1.

Fractionation was evidently very intense in the platy parts of the intrusion, which offered a large surface for cooling. Factor 1 may also be partly attributed to contamination, which raises the abundance of incompatible elements in magma.

Petäjäjärvi (60)

The platy intrusion at Petäjäjärvi is about 140 m wide; the other dimensions have not been established (Ohenoja 1986). The material of the intrusion was divided into two lithological groups, of which the most mafic one is richer in olivine. The rocks are dunites and harzburgites composed of olivine and orthopyroxene.

The material was examined on the basis of XRF data only. Moreover, the number of samples was too low for the mode of occurrence of the rock types to be established reliably.

The low sulphide contents in the Petäjäjärvi intrusion indicate weak sulphide mineralization (Appendix 2).

Kotkatsuo (62)

The Kotkatsuo intrusion has a maximum diameter of c. 200 m but the shape and depth are unknown. There are three lithological groups at Kotkatsuo. Because thin sections were not cut from all the samples the petrological description of the groups is incomplete. The rocks of groups 1 and 2 are melanorites and norites, and those of group 3 leuconorites; all have undergone intense amphibolization.

The groups occur in drill intersections as continuous portions. The rocks of group 1 are located in the southern part of the intrusion, those of group 2 in the middle and those of group 3 in the northern part. Hence, fractionation proceeded from south to north. It was probably cyclic, as suggested by the fairly large differences in SiO_2 and S levels between groups 1 and 2.

The magma did not contain sulphides at the time of injection, because the most mafic lithological group is so poor in sulphides. Sulphides were formed only during the crystallization of the rocks of group 2 (Appendix 2).

Koirusvesi (64)

The Koirusvesi intrusion has four lithological groups. The rocks of group 1 are dunites and lherzolites, and those of group 2 lherzolites and olivine websterites. Group 3 is composed solely of websterites, and group 4 contains norites and gabbronorites. The groups correspond by and large to the classification of Makkonen and Ekdahl (1984), who give a detailed petrological description of the rocks. The groups are best separated from each other in the coordinate system of factors 1 and 2 (Fig. 23). Factor 1 represents the fractionation between mafic minerals and plagioclase, and factor 2 the segregation of sulphides from magma. The ultramafic rocks of groups 1, 2 and 3 are separated from the norites along factor 1. According to factor 2, group 2 is rich in sulphides. Factor 3 cannot be interpreted unambiguously. However, it refers, at least partly, to the accumulation of clinopyroxene.

Lherzolites occur embedded in norites as a plate, about 100 m wide, together with websterites. The rocks of groups 1 and 2 constitute continuous portions in drill intersections, although they also alternate with each other. The rocks of group 3 are scattered, whereas those of group 4 occur in the more continuous portions.

The mode of occurrence and factor diagrams of the rocks suggest that magmatic evolution in

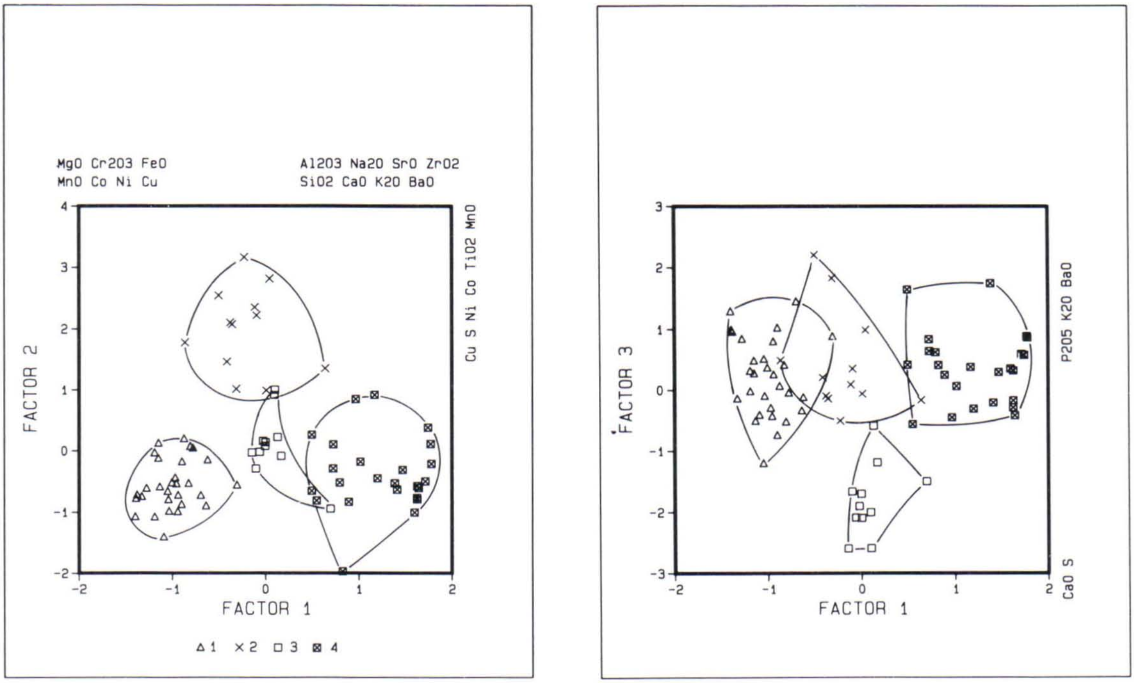

Fig. 23. Factor scores of the Koirusvesi data. 1 = dunites and lherzolites poor in sulphides, 2 = lherzolites moderately rich in sulphides, 3 = websterites with abundant clinopyroxene, 5 = norites.

the Koirusvesi intrusion was not a continuous process. The major culmination in the magmatic evolution was between groups 1 and 2, and between groups 3 and 4. This is compatible with the observations of Makkonen and Ekdahl (op. cit.), who proposed two separate magma injections for the intrusion.

The mean contents of TiO_2, SrO, K_2O and P_2O_5 in the norites are lower than those in the more mafic rocks, implying that the magmatic evolution was not due to the normal fractionation of mafic minerals (Appendix 2).

The relationship of websterites to lherzolites is also contrary to the normal fractionation trend, because the websterites are poor in BaO and P_2O_5. The high K_2O and CaO values can probably be ascribed to contamination and the accumulation of clinopyroxene. The dyke-like mode of occurrence of the websterites and their fine grain size suggest that these rocks do not represent the same crystallization series as lherzolites.

The rocks of group 2 are the richest in sulphides in the Koirusvesi intrusion. The rocks of groups 1 and 2 belong to the same crystallization series, indicating that the magma was not sulphide-saturated at the time of injection. Barren dunites and lherzolites were formed immediately after injection as a result of the accumulation of olivine. On account of the crystallization of olivine and fractionation the residual magma became enriched in sulphur, resulting in local segregation of immiscible sulphides.

10. Hitura environment

There are several intrusions with mafic and ultramafic rocks in the environment of Hitura. However, the present study deals only with the Hitura intrusion, which hosts about 10 M.t. of

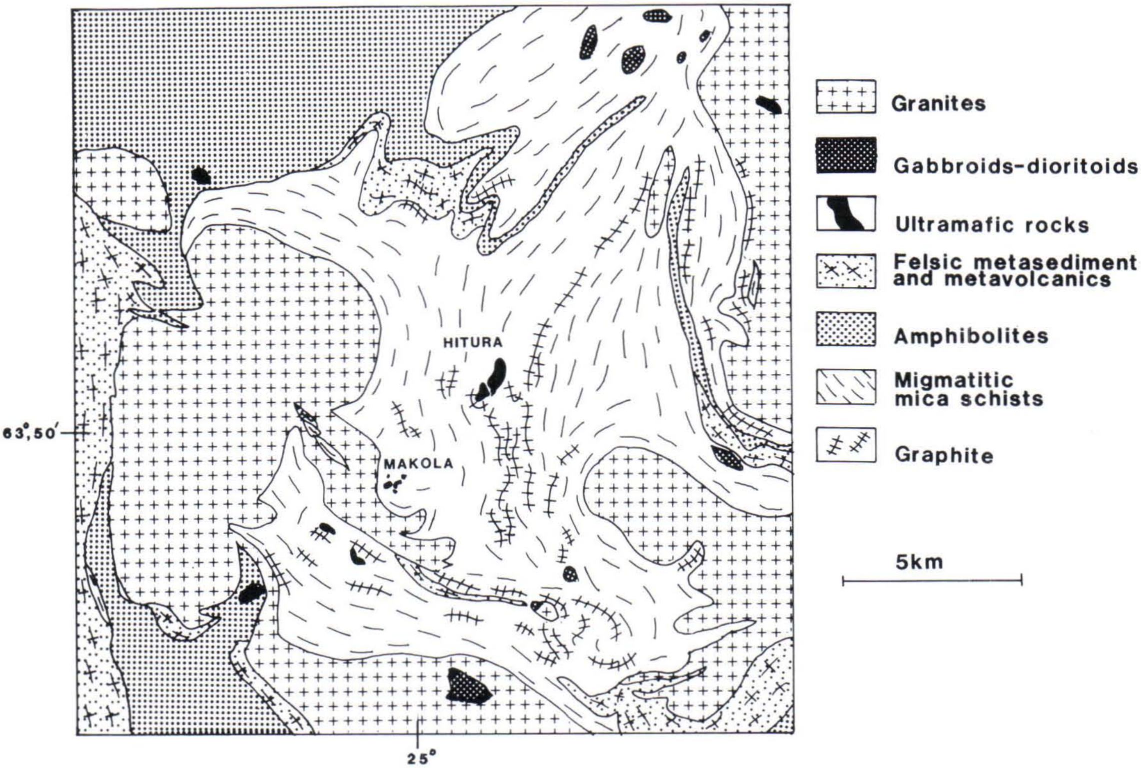

Fig. 24. Geology of the Hitura environment modified from the map of Isohanni et al. (1985).

ore assaying 0.5 % Ni (Isohanni *et al.* 1985). During 1941—1954 Ni-Cu ore was mined from the Makola occurrence at a distance of about 5 km from Hitura.

Figure 24 depicts the geological setting of the Hitura environment. Isohanni *et al.* (op.cit.) have classified the supracrustal rocks in the Nivala area into two groups and the plutonic rocks into three groups. The lower part of the supracrustals is composed of migmatitic mica gneisses that contain graphite-bearing and sulphide-bearing mica gneisses and amphibolites. These are the country rocks of the intrusions of Hitura and Makola. The amphibolites occur as elongated zones between the plutonic rocks and migmatic mica gneisses, where they exhibit some pyroclastic and lava structures. The upper group consists of two volcanic series with greywackes between them.

The volcanites are andesites and dacites, and often show primary structures. The oldest plutonic rocks in the Nivala area are ultramafites, which occur in association with the stratigraphically lowermost migmatitic mica gneisses. Syntectonic intrusive rocks younger than the ultramafites vary from gabbros to granites in composition. Heterogeneous granodiorites with mafic plutonic rocks or schist fragments as inclusions predominate. The rocks in the Hitura environment are intensely folded, and in places there are schollenmigmatites.

Hitura (66)

The Hitura intrusion, which measures c. 0.3 × 1.2 km on the surface plane, is the second largest ultramafic intrusion of the present study. Its depth has not been established, but the deepest drill intersections are at 550 m. The Hitura in-

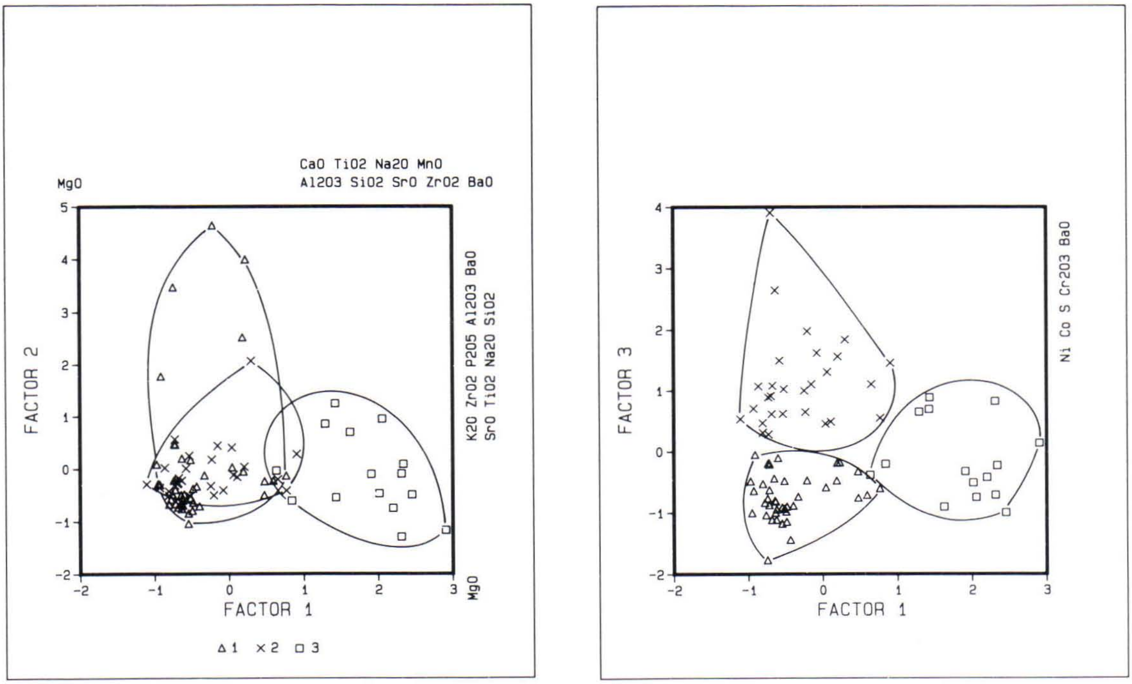

Fig. 25. Factor scores of the Hitura data. The petrographical classification of the groups is only indicative. 1 = dunites and lherzolites, 2 = dunites and lherzolites rich in sulphides, 3 = lherzolites.

trusion has three lithological groups. Their mineral compositions are unknown, because it was not possible to correlate the samples with the thin section data. According to Isohanni *et al.* (1985), the bulk of the intrusion is composed of serpentinized dunites and lherzolites. The intrusion is rimmed by amphibole rocks, which, however, were not included in the present study.

Group 3 has the highest scores of factor 1 and represents the most intensely fractionated rock types (Fig. 25). On account of the fractionation of olivine the residual melt became enriched in clinopyroxene and incompatible elements. Factor 2 resembles factor 1, both referring to two similar events. However, only three samples have high factor 2 scores, suggesting that the event occurred within a rather small area. The degrees of fractionation in groups 1 and 2 are similar along factor 1, but factor 3, which refers mainly to the fractionation of sulphides, separates them into individual groups. As shown by factor 3, chromite crystallized together with sulphides. The sampling density of the material of the present study was too low to permit the occurrence of the groups in the intrusion to be established with certainty. However, they appear to exist as independent rather than overlapping units.

It was not possible to correlate the groups with the classification of Isohanni *et al.* (1985), in which the rocks of Hitura are divided into four groups on the basis of Al_2O_3 content. Even though the materials were the same, the Al_2O_3 contents of the reanalysed samples differed from those in the material of Isohanni *et al.* (op. cit.). The difference in the Al_2O_3 values may be due to a change in the orientation of micas in the powder compacts (Papunen, pers. comm.)

A conspicuous feature of the material is the clear geochemical difference between the groups. According to Isohanni *et al.* (op. cit.), the zone richest in sulphides follows the margins of the northern part of the intrusion, which, in places, are contaminated.

The modes of occurrence of the groups may be a result of successive magma injections, although convection, too, is capable of producing separate magma types that differ from each other. According to Huppert and Sparks (1984), convection contemporaneous with crystallization may produce highly diverse magma types.

The shape and size of the Hitura intrusion are amenable to convection, and crystallization due to cooling and the resulting convection were most intense along the walls of the intrusion.

The amphibole rocks in the margins of the intrusion were formed as a result of rapid cooling. The intense fractionation caused by convection in the marginal parts of the intrusion may have contributed to the events described by factors 1 and 3, giving rise to the formation of rock types rich in sulphides and incompatible elements. According to Duke (1979), the amount of segregating sulphides is directly proportional to the amount of fractionating olivine.

11. Alavieska environment

The supracrustal rocks in the environment of Alavieska are sedimentary and volcanic schists. They occur in belts with extensive intrusion zones composed of granites, granodiorites, quartz diorites, diorites, gabbros and ultramafics between them (Salli 1961).

The sedimentary schists include quartz-feldspar schists, greywackes, conglomerates and mica schists. The quartz-feldspar gneiss resembles arkosite and often occurs in the contacts of the plutonic rocks. The greywackes are layered rocks with occasional quartz-feldspar gneiss fragments. In places the greywackes have conglomerate interlayers with various supracrustal rocks as clasts. Mica schists also occur in association with greywackes, both having the same composition. The volcanic rocks are uralite porphyrites, plagioclase porphyrites, silicic tuffites, volcanic breccias and agglomerates.

The intrusive rocks occur as round massifs between the schist zones. The intrusions form continuous compositional series from gabbros to granites. The gabbro-diorite intrusions are usually conformable to the schists, but the more silicic rocks often crosscut them. The gabbro-diorite intrusions frequently include ultramafic portions.

Alavieska (68)

The Alavieska intrusion is a roundish body with a maximum diameter of 4.5 km. The number of samples is small (56 samples) in relation to the size of the intrusion and thus gives only a very rough picture. The rocks of group 1 are amphibolitized gabbronorites in which orthopyroxene predominates over clinopyroxene. The group 2 rocks are amphibole gabbros. The mineral assemblage of group 3 is the same as that of group 1, except that the abundance of plagioclase is higher in the former.

Unpublished results of Häkli show that the rocks richest in sulphides are located in the southern margin of the intrusion. According to the present study, the rocks of group 1 prefer the southern part of the intrusion and the rocks of group 3 its northern part. Thus, the fractionation of magma advanced northwards towards the area of the most evolved rocks. No marked sulphide mineralization occurred in any lithological group, as deduced from the low values of S, Cu, Co, Zn and Ni (Appendix 2).

12. Toivakka and Kangasniemi environment

The environment of Toivakka and Kangasniemi lacks a published, detailed description of the geological set-up. Most of the rocks are granitoids emplaced during the Svecokarelian orogeny. Small schist portions are encountered among the granitoids (Nurmi *et al.* 1984). Some supracrustal rocks are associated with the intrusions of Toivakka and Kangasniemi.

Toivakka (72)

The Toivakka intrusion, which measures 2 × 5 km, is composed of four lithological groups. The rocks of groups 1 and 2 are mainly olivine gabbros containing plagioclase, orthopyroxene, clinopyroxene and olivine. Group 3 consists of gabbronorites with orthopyroxene and clinopyroxene. The rocks of group 4 are diorites with plagioclase and pyroxenes as essential minerals. The rocks have undergone amphibolitization, and the boundaries between the groups are gradual.

According to unpublished studies of Häkli, the zones richest in sulphides are located in the northern part of the intrusion. The present study confirms this, showing that the more mafic rocks, which are the richest in sulphides, occur in the northern part of the intrusion. However, the sulphide values are modest (Appendix 2).

Kangasniemi (74)

The Kangasniemi intrusion is a roundish body with a maximum diameter of 4.5 km. Only 27 samples were available from the intrusion, in which the lithological composition varies from olivine gabbros to diorites. Plagioclase is the main mineral in all rocks, and orthopyroxene predominates over clinopyroxene.

Unpublished results of Häkli show that the samples richest in sulphides derive from the central parts of the intrusion. However, the average sulphide content is low (Appendix 2).

13. Liakka environment

The Liakka intrusion is located in an east-west trending schist belt characterized by quartzites, dolomites, mafic volcanics and phyllites (Fig. 26). The quartzites are probably part of an Upper Jatulian formation with dolomite as interlayers. The quartzites are overlain by tuffitic volcanics. Highest in the stratigraphy are the phyllites.

There are no other intrusions of similar composition or size in the vicinity of the Liakka intrusion, although farther south there are several smaller intrusions that are probably genetically related to each other.

Liakka (70)

The Liakka intrusion is a roundish body c. 1.8 km in diameter. Its depth extension has not been established but the deepest drill intersection is at c. 220 m. The intrusion is layered such that the ultramafic rocks are located in its basal parts and the mafic rocks in its upper parts. The composition also varies laterally, the abundance of ultramafic rocks being highest in the eastern part of the intrusion (Fig. 26) (Kuronen 1982).

There are four lithological groups in the Liakka intrusion. Group 1 is composed of olivine websterites with olivine, orthopyroxene, clinopyroxene and occasional plagioclase. The rocks of groups 2 and 3 are websterites and gabbronorites with variable abundances of olivine and plagioclase. In group 2 orthopyroxene predominates over clinopyroxene. Group 3 has even more orthopyroxene, and in places plagioclase occurs as cumulus phase whilst apatite forms prisms

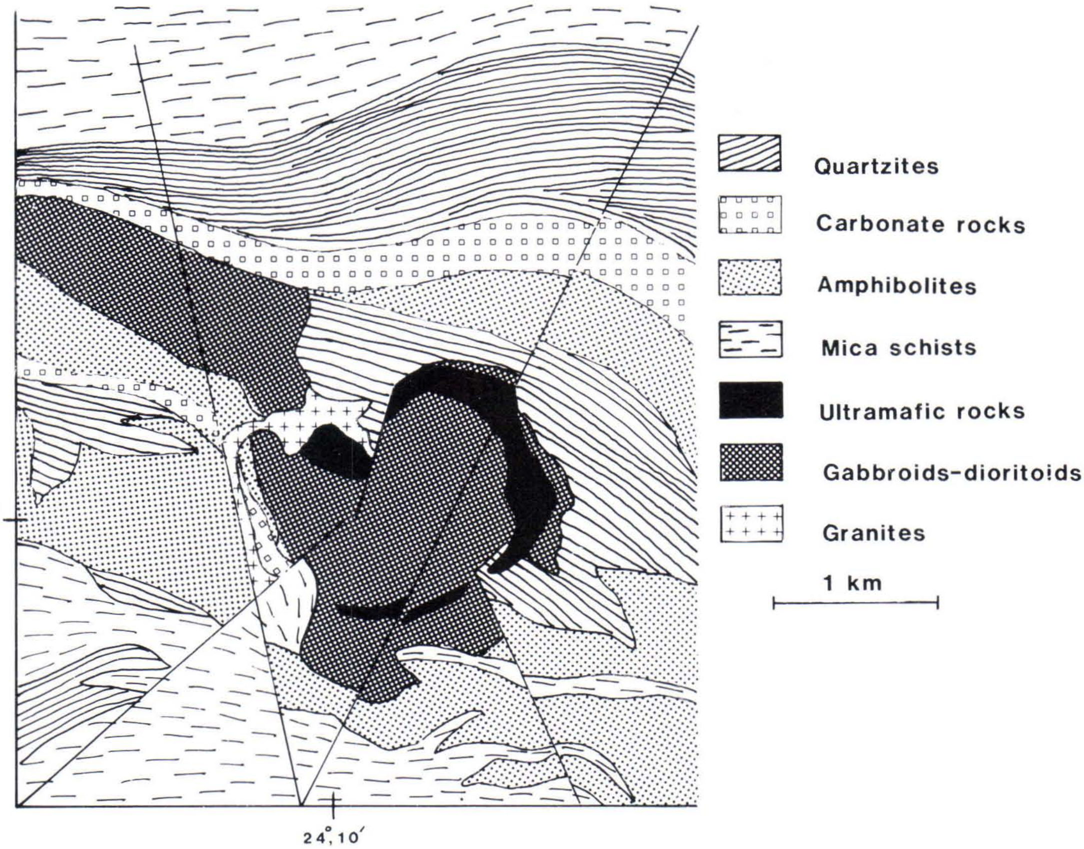

Fig. 26. Geology of Liakka modified from the map of Kuronen (1982).

measuring c. 1 mm. Occasionally orthopyroxene has clinopyroxene inclusions. The gabbros of group 4 have plagioclase as the predominant mineral. Pyroxenes and amphiboles occur in varying proportions. There is thus a certain petrological grading between groups 3 and 4.

All the lithological groups of the Liakka intrusion are shown in Fig. 27. The clustering of the gabbros of group 4 is clearest along factor 1, which refers to the fractionation of plagioclase and mafic minerals, in accordance with the petrographic differences between group 4 and the other rocks. Moreover, group 4 has high scores of factor 2, which is interpreted as the magmatic evolution of the rock.

Groups 1—3 are shown in Fig. 28. The samples of group 1 are most clearly discriminated from the other lithological groups along factor 1, indicating that the segregation of sulphides was most intense in the most mafic rocks. Groups 2 and 3 cover the same compositional area along factor 2, which represents the enrichment of the residual magma in incompatible elements. However, groups 2 and 3 are separated along factor 3, indicating that plagioclase and the mafic minerals fractionated between the groups.

The magmatic evolution culminated at Liakka between the rocks of group 4 and those of the other groups. In places group 4 is associated with the other groups, but most often it occurs as continuous portions. The difference in composition and the separate mode of occurrence suggest that the rocks of group 4 were injected as a separate phase. Since these rocks are located in the upper parts of the intrusion in some drill intersections, this magma injection was the second one.

However, a similar overlapping sequence could also be ascribed to crystallization and convection (cf. Girardi *et al.* 1986). In that case, the rocks of group 4 would have formed during the crystallization of plagioclase. This is feasible to a certain extent, because there is some petrological grading between groups 3 and 4. Orthopyroxene and plagioclase would then have been the minerals to fractionate. Owing to the difference in the densities of the minerals, fractionation coincidental with convection produced group 4 rocks rich in plagioclase.

Group 1 is the richest in sulphides. The magma contained small amounts of sulphides when injection started, but later sulphide segregation declined.

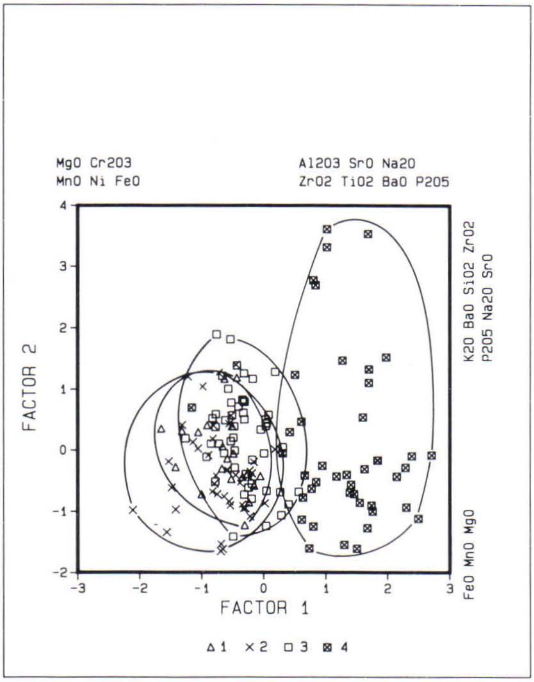

Fig. 27. Factor scores of the total Liakka data. 1 = olivine websterites, 2 and 3 = websterites, 4 = gabbronorites.

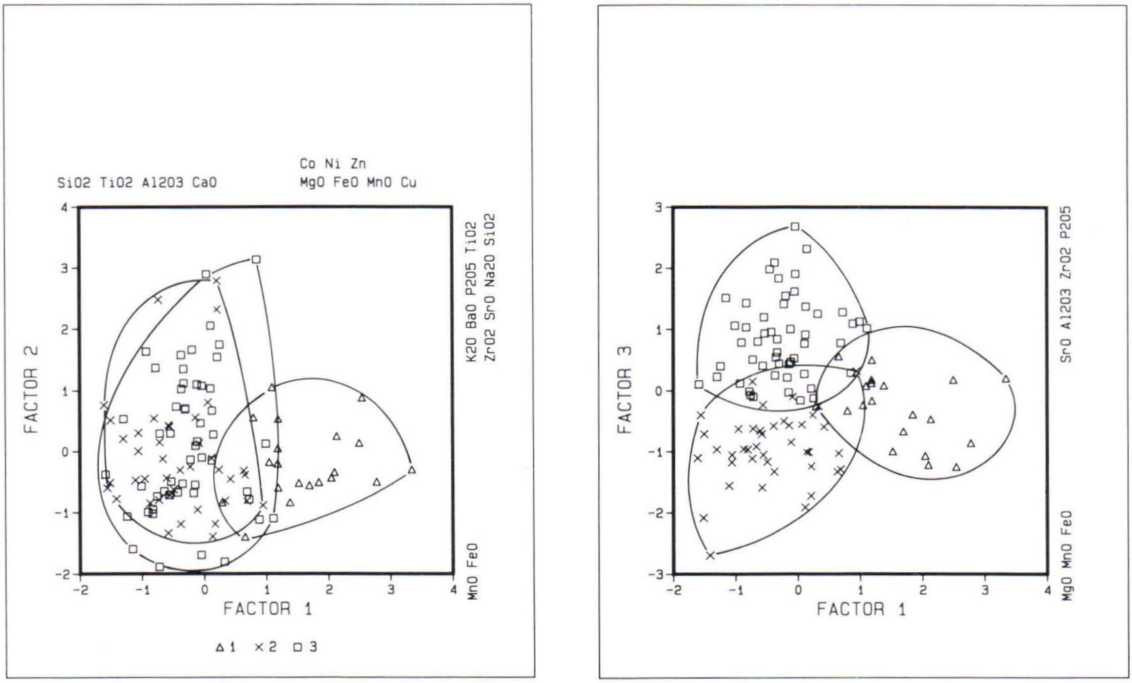

Fig. 28. Factor scores of the Liakka data with group 4 omitted. 1 = olivine websterites, 2 and 3 = websterites.

8. CLASSIFICATION OF THE INTRUSIONS

The intrusions were classified on the basis of factors into types that differ in mode of differentiation. The thirteen factor types described in chapter 6 were used as clustering variables, whose value depended on the percentage of explanation of the factors. Thus, for example, the third factor of Rottapäkki was placed in factor group 1, and got a value of 10, because its percentage of explanation was 10 (Appendix 1).

The intrusions were classified with the aid of hierarchical clustering analysis (BMDP 2M) (Fig. 29). The figure shows the three major groups, which from top to bottom are: peridotite intrusions, gabbro intrusions and peridotite-norite-gabbro intrusions. As a rule, differentiation advanced in the field of olivine and pyroxenes in the peridotite intrusions with the consequence that the abundance of gabbro differentiates is

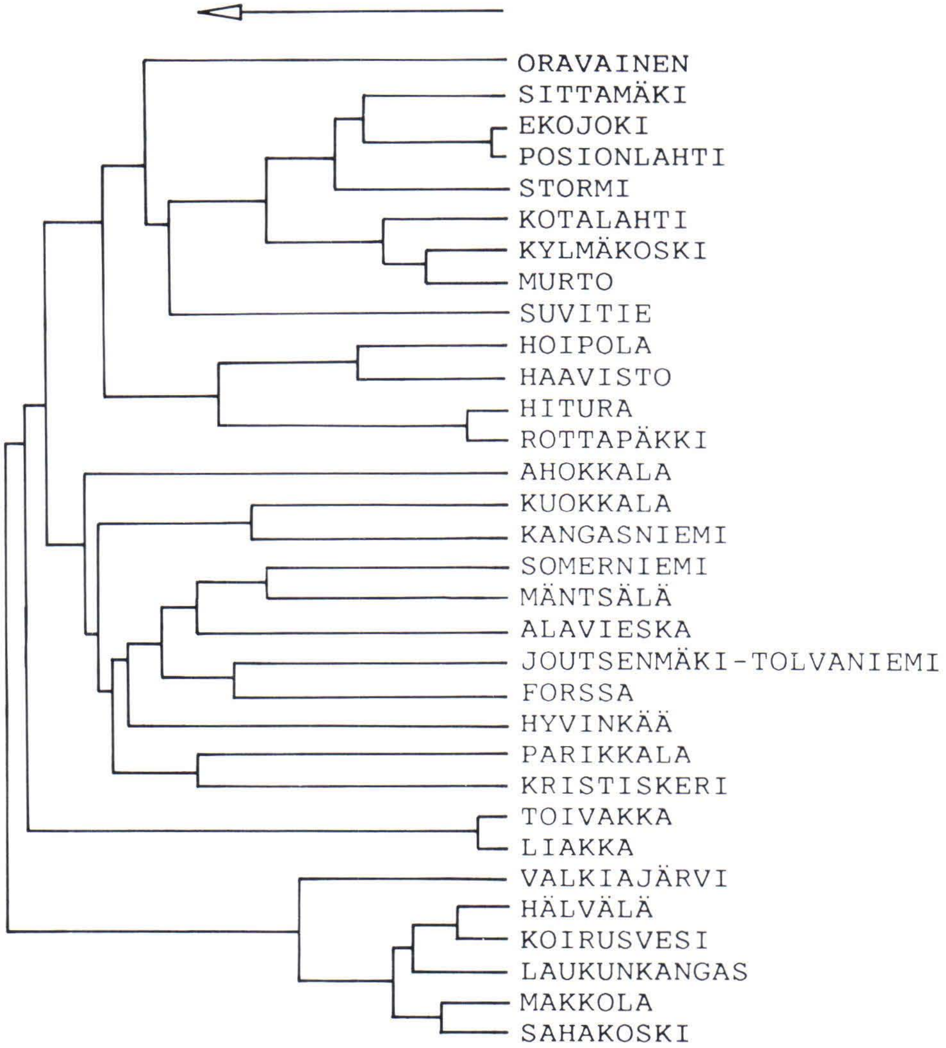

Fig. 29. Dendrogram depicting the classification of the intrusions. There are three major groups in the dendrogram, and the amalgamated distance between the intrusions increases in the direction indicated by the arrow.

low. Clinopyroxene predominates over orthopyroxene. Intrusions of this type favour the Vammala environment and are thus called the Vammala type (Fig. 9). In the peridotite-norite-gabbro intrusions the differentiation advanced from peridotites to norites and gabbros, and plagioclase replaced clinopyroxene as a cumulus mineral at an early stage. The intrusions contain abundant norites and gabbros. In places, peridotites and norites represent different magma injections. Peridotite-norite-gabbro intrusions occur in the areas of Kotalahti, Laukunkangas and Ahlainen.

The geochemical material from Kotalahti studied in the present work contains only the most mafic rocks of the intrusion. However, as shown by more comprehensive petrological studies, the Kotalahti intrusion contains both peridotites and gabbros (Fig. 21). At the early crystallization stages plagioclase crystallized in the interstices of olivine and orthopyroxene. Accordingly, the Kotalahti intrusion should be included in the same group as Laukunkangas. The materials from Kristiskeri and Rottapäkki are incomplete, because the Kristiskeri material lacks peridotite members and the Rottapäkki material norite members. In terms of lithological types, the intrusions of Kristiskeri and Rottapäkki should also be included in the peridotite-norite-gabbro group. The intrusions of this group are called Kotalahti type in allusion to the best-known of these intrusions. Since not all the intrusions were included in the classification based on factors, the Kotalahti and Vammala types are listed in the following. The intrusions of the Kotalahti-type are Kristiskeri, Sahakoski, Hyvelä, Rottapäkki, Hälvälä, Makkola, Laukunkangas, Kotkatsuo, Valkiajärvi, Kotalahti, Petäjäjärvi and Koirusvesi. Those of the Vammala-type are Oravainen, Murto, Sittamäki, Hoipola, Posionlahti, Ekojoki, Stormi, Haavisto, Suvitie, Kylmäkoski and Hitura.

The classification of the intrusions in the Raahe-Ladoga belt exhibits features similar to those noted in the classifications of Häkli *et al.* (1978) and Tontti *et al.* (1982). According to Tontti *et al.* (op. cit.), the intrusions of Hitura and Kotalahti belong to the same group, but that of Laukunkangas is from a different group. However, the Kotalahti and Laukunkangas intrusions resemble each other petrologically and are therefore included in the same group in the present study. Note also that in the Koirusvesi intrusion, which is located in the Kotalahti area, abundant clinopyroxene crystallized in places, a feature typical of the Vammala-type intrusions.

The intrusions of Liakka and Toivakka do not fit into any of the above groups. The material from Toivakka is small relative to the size of the intrusion, and so the factors may give a biased picture. The material from Liakka is fairly comprehensive, which means that the factors probably describe a differentiation event distinct from those experienced by the other intrusions. The factors referring to the differentiation at Liakka form groups that refer to the differentiation of either gabbro or peridotite intrusions.

9. NORMATIVE COMPOSITIONS

Figures 30 and 31 show the normative compositions of the lithological groups of the Kotalahti and Vammala types. An effort was made to calculate the compositions from rocks with plagioclase and clinopyroxene as intercumulus minerals, because these rocks best reflect the abundance of normative diopside and anorthite in the parent magma. The compositions refer to the molecular norms (Kaivosoja & Koivumaa 1984, Morse 1980). Nevertheless, the normative compositions calculated from the cumulates are indicative only, because they do not correspond di-

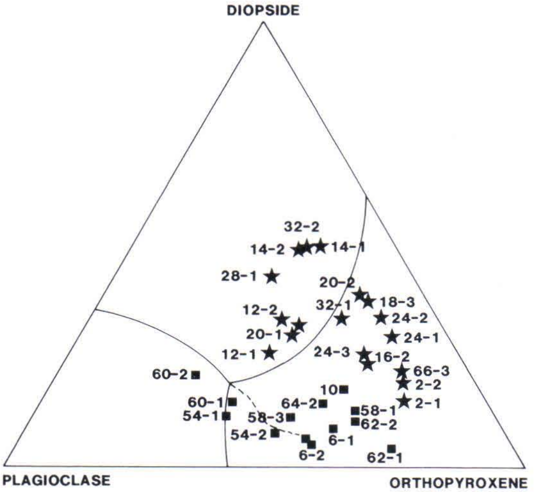

Fig. 30. Normative compositions of the lithological groups. The lithological groups are provided with the location code of the intrusion and the code of the lithological group. The location codes are given in Table 1. Square = Kotalahti-type rocks, and star = Vammala-type rocks. Figure depicts olivine-saturated faces of the basalt tetrahedron projected onto the plagioclase-diopside-orthopyroxene triangle. The liquidus surfaces are based on determinations from the natural material (Irvine 1971). The ternary crystallization path, which is outside the plane of the figure, is marked with a dashed line.

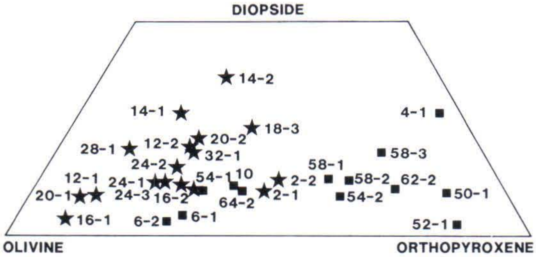

Fig. 31. Normative compositions of the lithological groups in the olivine-diopside-orthopyroxene triangle. The location codes of the lithological groups are given in Table 1. Square = Kotalahti-type rocks, and star = Vammala-type rocks.

rectly to the composition of the parent magma (Irvine 1974).

The crystallization orders of the Vammala and Kotalahti types can be examined with the aid of Fig. 30, which depicts olivine-saturated faces of the basalt tetrahedron projected onto the plagioclase-diopside-orthopyroxene plane. The composition of ultramafic magma plots in the olivine field, and olivine is the first mineral to crystallize. As the fractional crystallization advances, the composition of the residual melt moves into the orthopyroxene field as a result of reactions between olivine and orthopyroxene. In the orthopyroxene field the composition of the melt moves onto the cotectic surfaces between either orthopyroxene and plagioclase or orthopyroxene and clinopyroxene. Should the normative diopside predominate markedly over normative plagioclase, the composition of the residual melt moves onto the boundary surface between orthopyroxene and clinopyroxene. The crystallization order is now olivine, orthopyroxene, clinopyroxene. In the reverse case, the composition moves onto the boundary between orthopyroxene and plagioclase, and the crystallization order is olivine, orthopyroxene, plagioclase (Irvine 1970).

Since Vammala-type magmas are rich in normative diopside they tend to fractionate towards the clinopyroxene field. In contrast, magmas of the Kotalahti type fractionate towards the plagioclase field, thus resulting in two different crystallization series.

Figure 31 shows the normative compositions of the Kotalahti and Vammala-type rocks in the olivine-diopside-orthopyroxene triangle. The Kotalahti-type rocks are markedly richer in normative orthopyroxene than are the Vammala-type rocks.

10. AREAL VARIATION IN COMPOSITION

The compositional differences between the intrusions were examined only on the basis of the elements with satisfactorily accurate analytical data. These were SiO_2, TiO_2, Al_2O_3, Cr_2O_3, FeO, MgO and CaO. For each element a regression curve of the second order was drawn as a function of MgO to serve as a mean level of comparison (Figs. 32—37).

The scatter of the SiO_2 content is lower in the ultramafic rocks than in the more felsic rocks (Fig. 32). The scatter is fairly high in the MgO range of 20—25 %, which is where the melanorites, pyroxenites and peridotites plot. The variation in SiO_2 contents is ascribed to the difference in SiO_2 values in olivine, pyroxenes and plagioclase. There are no areal differences in composition. The rocks at Oravainen show high mean SiO_2 values as a result of contamination,

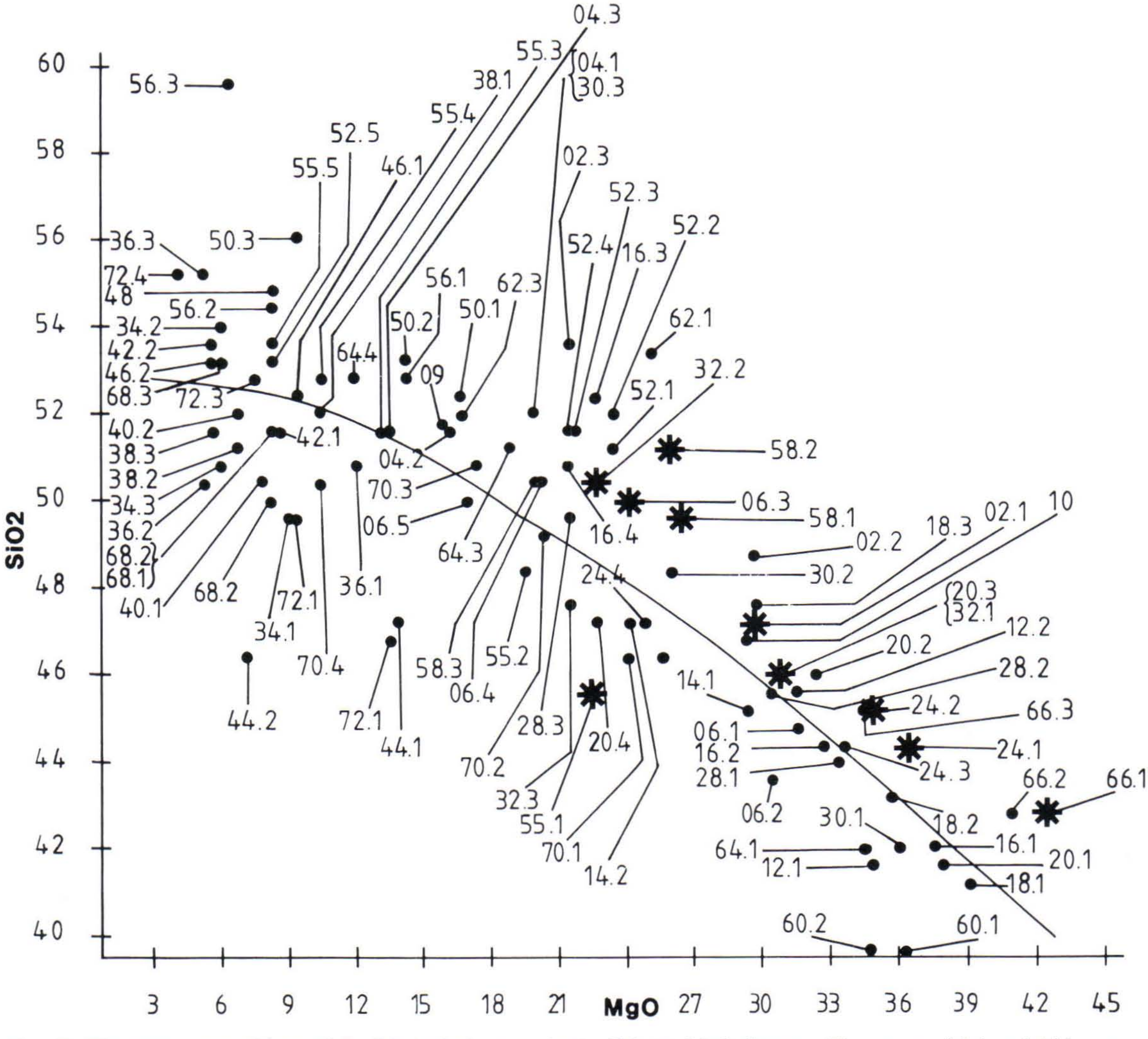

Fig. 32. The mean compositions of the lithological groups in the SiO_2 vs. MgO diagram. The groups rich in sulphides are marked with an asterisk. This diagram and other similar diagrams have a second order regression curve calculated from the total data. The location codes of the lithological groups are given in Table 1.

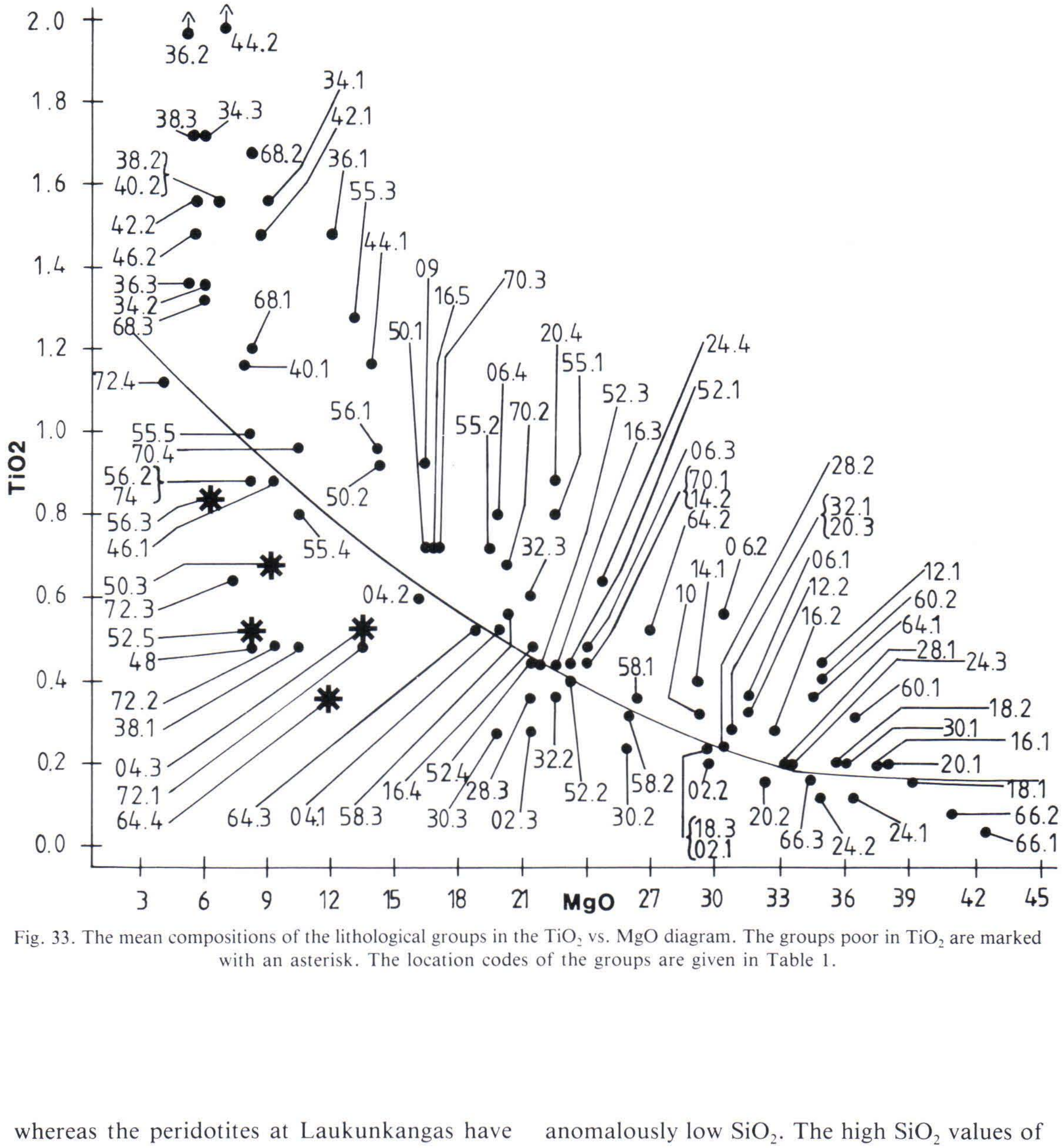

Fig. 33. The mean compositions of the lithological groups in the TiO_2 vs. MgO diagram. The groups poor in TiO_2 are marked with an asterisk. The location codes of the groups are given in Table 1.

whereas the peridotites at Laukunkangas have anomalously low SiO_2 contents. The peridotites of the intrusions of Oravainen, Stormi, Kylmäkoski, Kotalahti and Hitura, which host nickel occurrences, also have abundant SiO_2 in relation to MgO.

The bulk of the more felsic gabbroic rocks plot close to the SiO_2-MgO regression curve. However, the rocks of Parikkala and Toivakka have anomalously low SiO_2. The high SiO_2 values of the group 3 rocks of Hälvälä and Valkiajärvi are due to contamination, as suggested by their mode of occurrence and factors.

There is no difference in TiO_2 contents between the areas (Fig. 33). The fluctuation in TiO_2 is highest in the rocks of the gabbro group, the average TiO_2 values in the gabbros varying between 0.4 and 2.2 %. TiO_2 is anoma-

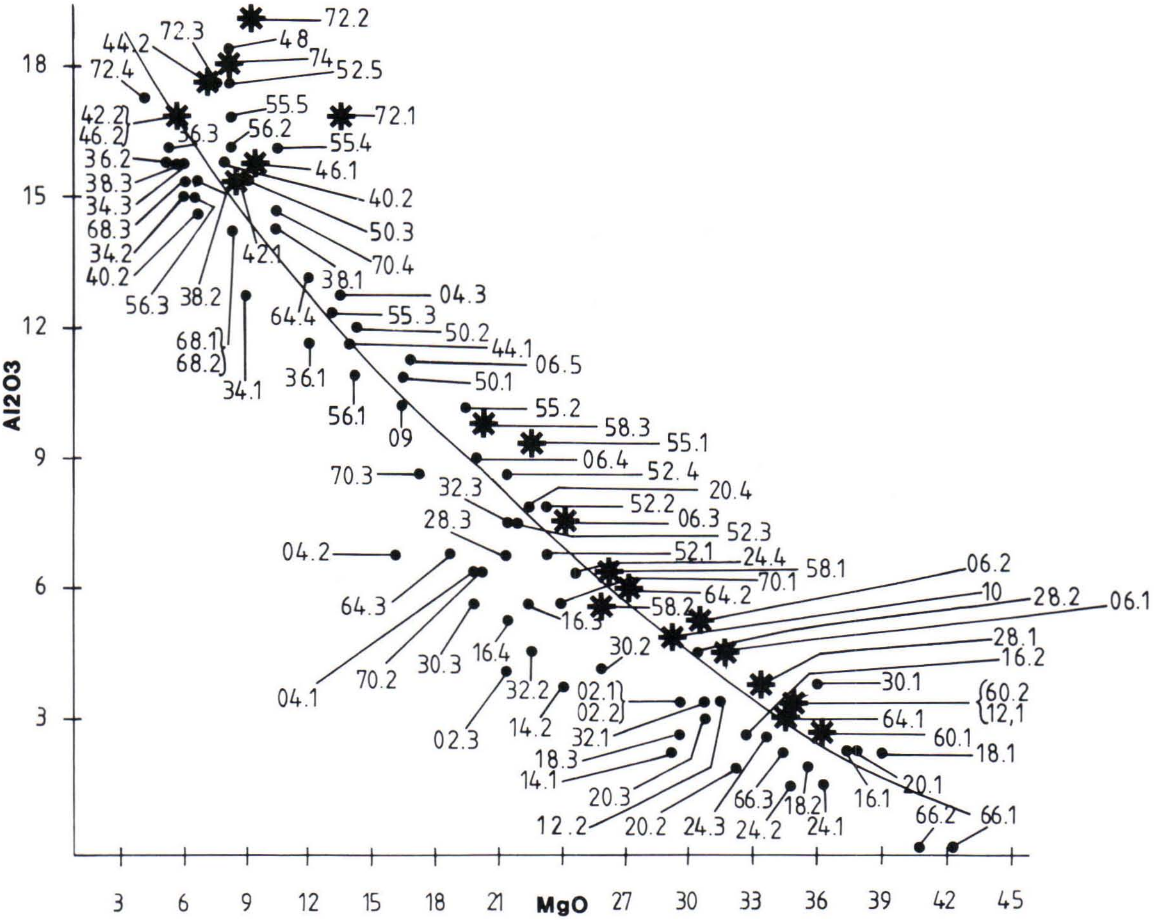

Fig. 34. The mean compositions of the lithological groups in the Al_2O_3 vs. MgO diagram. The gabbro intrusions rich in Al_2O_3 and the Kotalahti-type intrusions are marked with an asterisk. The location codes of the groups are given in Table 1.

lously high in the group 2 rocks at Forssa and Parikkala. The large gabbro intrusions are commonly richer in TiO_2 than are the gabbro differentiates of the more mafic intrusions. The latter rocks, which are poor in TiO_2, occur in group 4 of Koirusvesi, group 3 of Kristiskeri, group 5 of Makkola, group 3 of Hälvälä and group 3 of Valkiajärvi.

Of the ultramafic rocks, the peridotites of Laukunkangas are anomalously rich in TiO_2. Group 1 at Murto and group 2 at Sahakoski also exhibit high TiO_2 values.

The Al_2O_3 contents show marked areal differences (Fig. 34). The rocks in the environment of Kotalahti and Laukunkangas are generally rich in Al_2O_3, and plot above the regression curve, whereas the other ultramafics plot on both sides of the curve. The Sahakoski intrusion in the Ah-

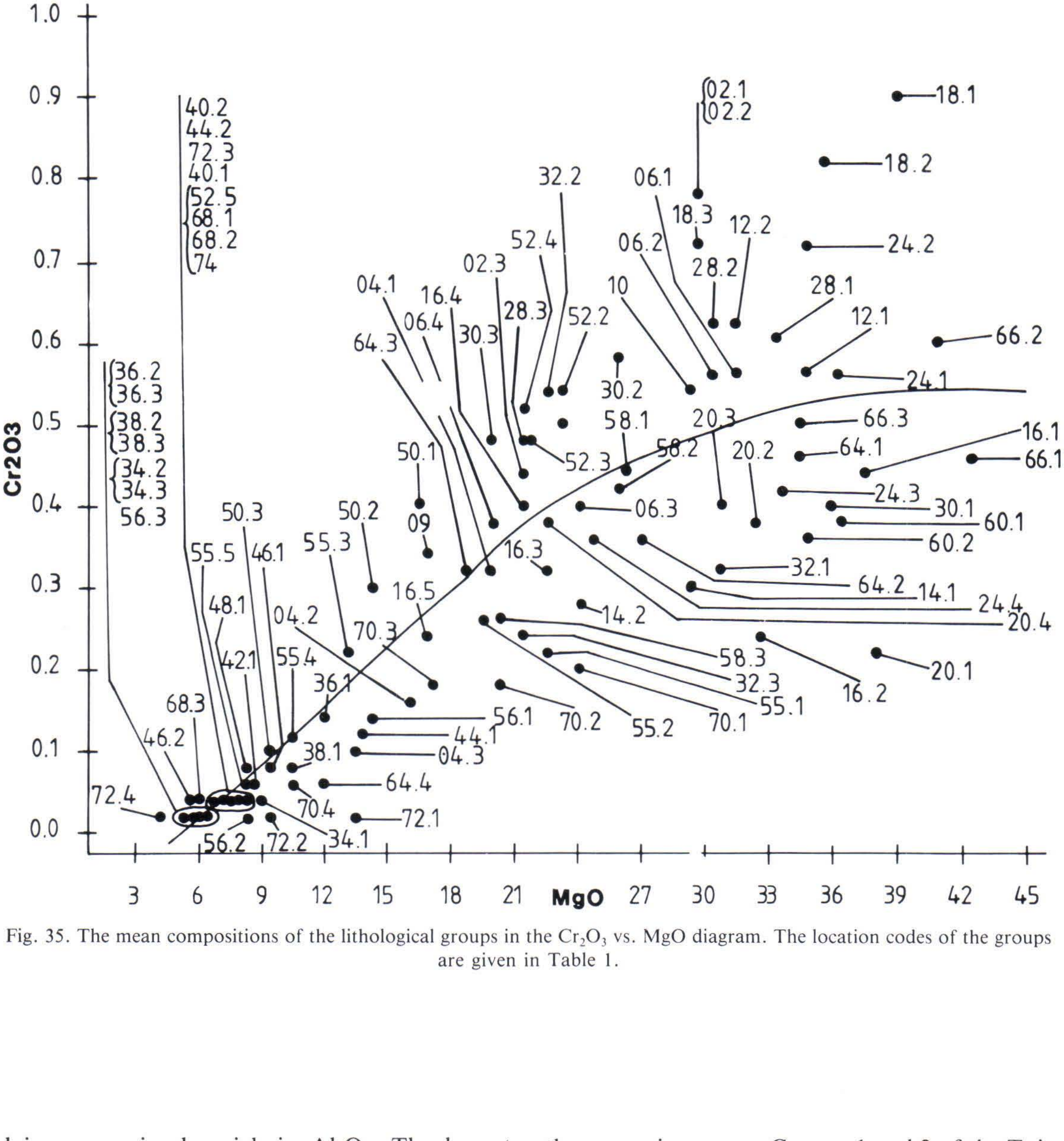

Fig. 35. The mean compositions of the lithological groups in the Cr_2O_3 vs. MgO diagram. The location codes of the groups are given in Table 1.

lainen area is also rich in Al_2O_3. The lowest Al_2O_3 values are in the ultramafics of the Vammala area and of Hitura. The areal differences in Al_2O_3 are best revealed by the large gabbro intrusions, because the bulk of the lithological groups of Forssa, Somerniemi, Hyvinkää, Mäntsälä and Alavieska plot below the regression curve. The lithological groups of Ahokkala, Parikkala and Joutsenmäki-Tolvaniemi plot above the regression curve. Groups 1 and 2 of the Toivakka intrusion, which is located in the area of the central Finland granite batholite, are anomalously rich in Al_2O_3.

The Cr_2O_3 levels do not show areal differences, although there are differences in the variation in Cr_2O_3 (Fig. 35). The variation in Cr_2O_3 is high in the ultramafics of the Vammala area, where these rocks exhibit both the highest and

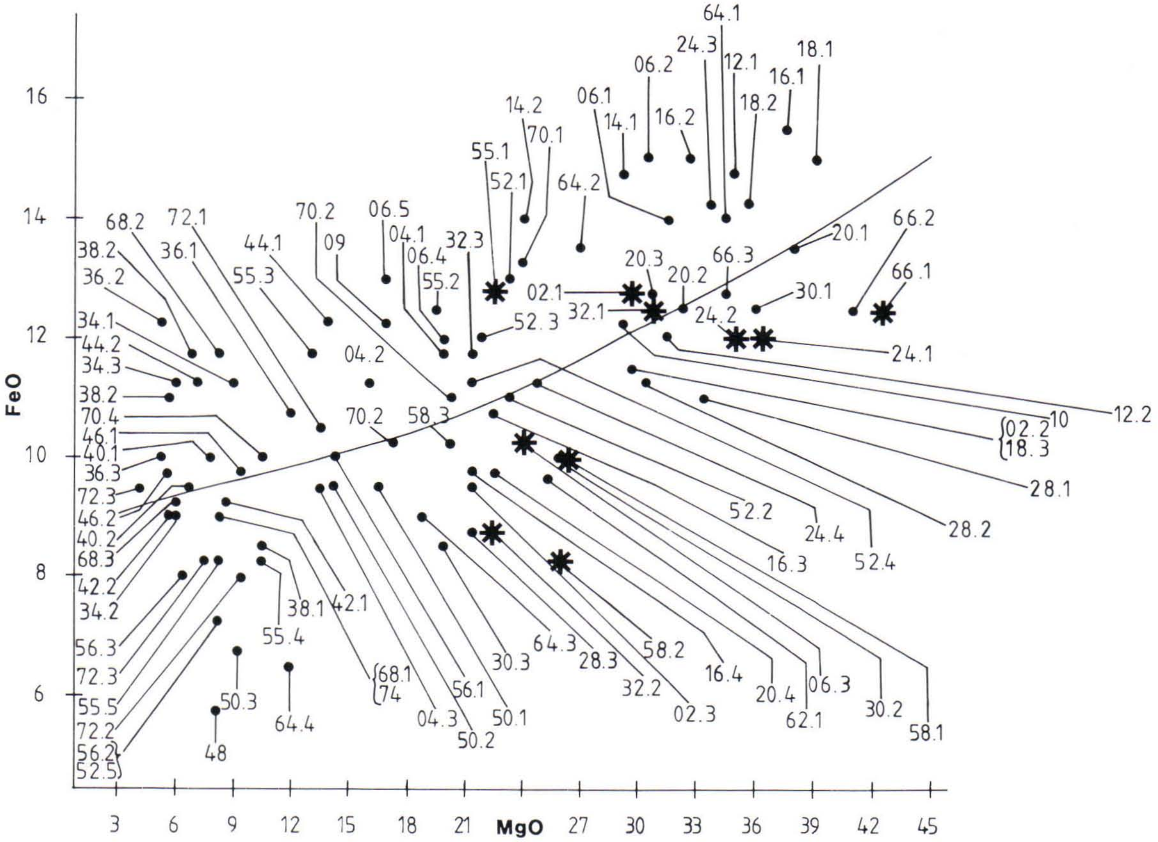

Fig. 36. The mean composition of the lithological groups in the FeO vs. MgO diagram. The groups rich in sulphides are marked with an asterisk. The location codes of the lithological groups are given in Table 1.

the lowest Cr_2O_3 contents encountered (group 1 at Posionlahti and group 2 at Ekojoki, respectively). The Cr_2O_3 content in the Oravainen intrusion is also fairly high.

The FeO contents do not show areal differences, and the variation is similar in both mafic and ultramafic rocks (Fig. 36). Group 2 of Kotalahti, group 4 of Koirusvesi and the Kuokkala intrusions are anomalously low in FeO. The large gabbro intrusions are richer in FeO than the late differentiates of the more mafic intrusions. The late differentiates of the gabbro class poor in FeO include group 4 of Koirusvesi, group 3 of Hälvälä, group 5 of Makkola, groups 2 and 3 of Valkiajärvi, and groups 4 and 5 of Laukunkangas.

The rocks of the intrusions hosting nickel occurrences are also low in FeO.

The CaO contents in the Vammala peridotites

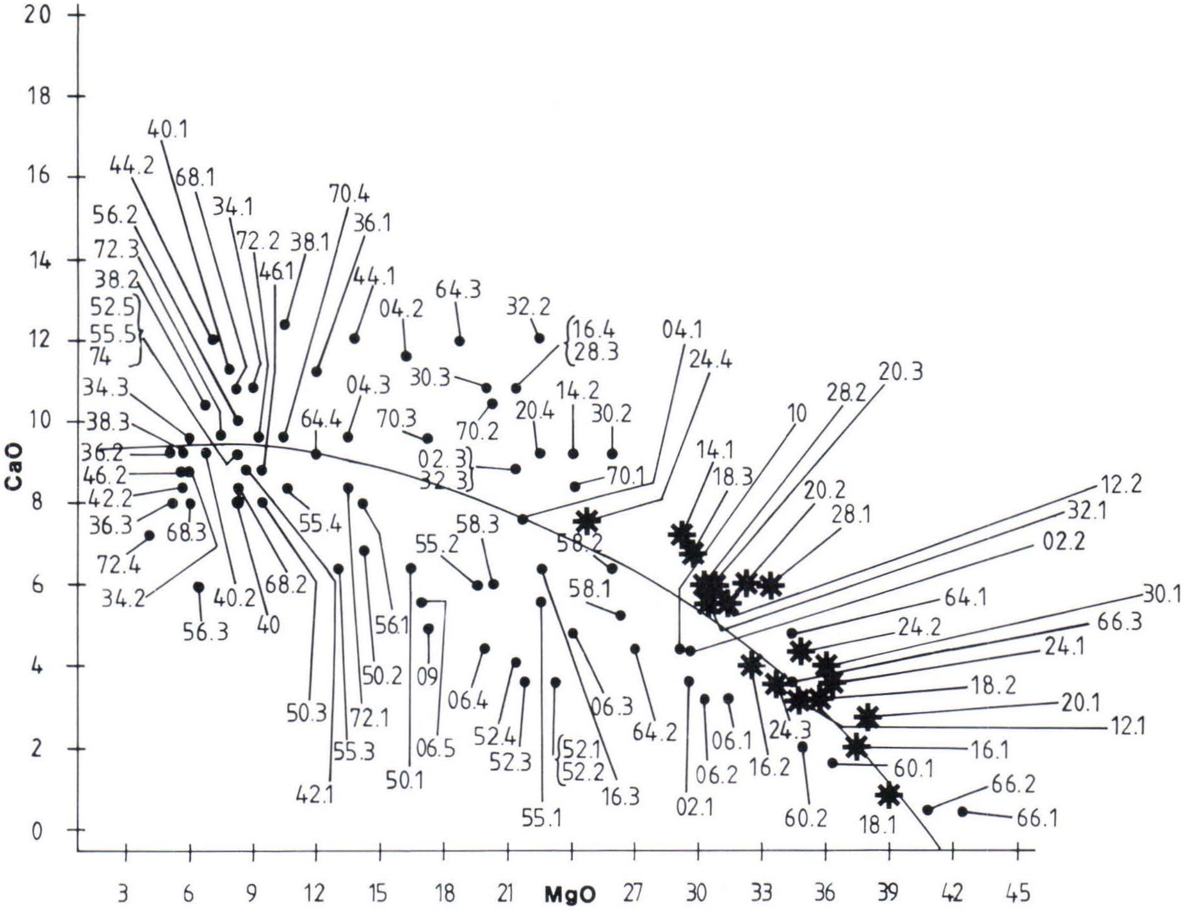

Fig. 37. The mean compositions of the lithological groups in the CaO vs. MgO diagram. The mean compositions of the Vammala-type rocks are marked with an asterisk. The locations codes of the groups are given in Table 1.

are almost invariably higher than elsewhere. In Fig. 37 the lithological groups of Ekojoki, Haavisto, Stormi and Suvitie plot above the regression curve. The rocks of Kylmäkoski are also rich in CaO. The variation in CaO is highest in the compositional range of norites and pyroxenites.

11. ORE POTENTIAL OF THE ROCKS

The ore potential of the intrusions and rocks was studied by comparing the rocks rich in sulphides with those poor in sulphides. The comparison was conducted on each intrusion separately because of the variation in concentration levels between the intrusions.

The samples of each study target were divided into two groups on the basis of their sulphide content. The scores of the sulphide factor that were affected only by the values of Cu, Ni, Co and S were used as a classification variable. Since the distribution of the sulphide content differed slightly in each intrusion the boundary between these two groups was set at a point at which the slope of the cumulative frequency distribution started to decline clearly. Hence, depending on the intrusion, 20—50 % of the samples were placed in the ore-potential group and the remainder in the sulphide-free group.

The sliding average was then calculated for each variable. The samples were arranged in order of increasing MgO values, and the sliding averages were calculated from five samples if the total number of samples was less than 40. If not, the sliding averages were calculated from nine samples. Finally, sliding averages were drawn for ore-potential and sulphide-free groups on an X-Y diagram with MgO as abscissa. The results are given in Appendix 3.

The ore-potential rocks are characteristically richer in SiO_2 and poorer in FeO than the sulphide-free groups. This is evident in the intrusions of Sahakoski, Ekojoki, Stormi, Kylmäkoski and Kotalahti. However, in the Hitura intrusion the situation is the reverse, because the ore-potential rocks contain less SiO_2 than the others. Moreover, the Cr_2O_3 contents increase as the sulphide content increases, implying that the factors which controlled the sulphide mineralization differed from those effective in the other intrusions. In the Oravainen intrusion the situation is similar, although the levels of SiO_2 and FeO vary. In the Kotalahti intrusion, too, the increase in Cr_2O_3 is associated with sulphide mineralization.

The differences in the concentrations of incompatible major and trace elements between the ore-potential and sulphide-free groups of all intrusions are similar. The differences are not, however, equal, although when the ore potential increases the values of TiO_2, Al_2O_3 and P_2O_5 decline. A similar, but less distinct concentration trend is shown by SrO and ZrO_2.

In the Stormi intrusion, as at Kylmäkoski, the CaO content correlates positively with the sulphide content.

In the mafic intrusions, the variations in concentrations are partly the reverse of those in the ultramafic intrusions. In the Joutsenmäki-Tolvaniemi and Laukunkangas intrusions the SiO_2 contents of the ore-potential rocks are lower and the FeO contents higher than in the sulphide-free rocks. What is more, the Al_2O_3, CaO, SrO, Na_2O and ZrO_2 values in the ore-potential rocks of Laukunkangas are lower than the average.

Ore potential was also studied in terms of the whole material. The lithological groups richest in sulphides were separated from the material, and their contents were compared with the general concentration levels. High sulphide contents occur in group 1 of Oravainen, group 3 of Sahakoski, group 1 of Ekojoki, groups 1 and 2 of Stormi, groups 1 and 2 of Kylmäkoski, groups 1 and 4 of Laukunkangas, group 2 of Kotalahti and group 2 of Hitura. These groups are rich in SiO_2 and poor in TiO_2, Al_2O_3 and FeO (Figs. 32—36). The Laukunkangas intrusion is, however, different, for it shows the reverse variation in concentrations.

Finally, all the above groups were pooled and their contents compared with those of the rest of the material. Sliding averages were calculated for each variable in both macrogroups and compared with each other. Except for SiO_2 and FeO, the overlapping of the elements in the groups was so high that it was difficult to distinguish between the groups. Therefore, only the SiO_2 and FeO contents of the ore-potential and sulphide-free rocks are given in Appendix 3.

The above phenomena are ascribed to the relationship between the elements incorporated in silicates and in sulphides. Since the contents are either positively or negatively correlated, the relations shown in Appendix 3 should also be reflected in the factors. The sulphide factors of the intrusions of Oravainen, Stormi, Haavisto, Kylmäkoski, Laukunkangas, Kotalahti and Hitura indicate the same events as Appendix 3, but less systematically.

The statistical significance between the groups was tested with the aid of a regression model of the first order. This was done by calculating the regression equation for the elements of both groups with the least squares method using MgO as an independent variable. The program also tested the difference between the groups in terms of each dependent element and gave the ratio of the variances of the groups as F values, thus allowing the significance of the differences to be determined (P = probability) (Dixon 1983).

Not all the differences reach a significance level of 0.95. Even so, some of these differences were dealt with in this context because of their similarity to the significant differences. The low significance of some variables may be ascribed to the unsuitability of the regression model (Davis 1973).

12. COMPOSITION OF OLIVINE AND ORTHOPYROXENE

Figure 38 shows the forsterite and Ni contents of olivine. The Ni to forsterite ratio of the olivines is higher in the Kotalahti-type intrusions than in the Vammala-type intrusions. The olivines of the Stormi cortlandites have high Ni contents but, because of their exceptional petrology, they were not included in the comparison (cf. Häkli *et al.* 1979).

The differences in olivine composition between the ore-potential and barren intrusions are similar in the Kotalahti and Vammala types. The barren intrusions of both types have low Ni in olivine.

In composition the orthopyroxene exhibits the same regularity as olivine, because the orthopyroxene of the barren intrusions is generally low

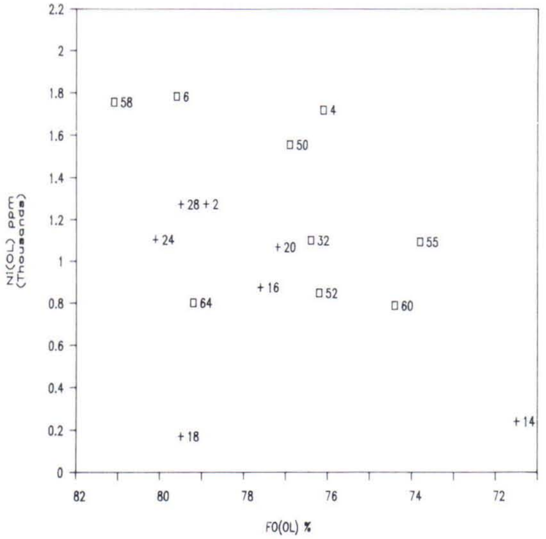

Fig. 38. Forsterite and nickel contents of olivine by intrusion. Square = Kotalahti-type targets, cross = Vammala-type targets. The location codes of the intrusions are given in Table 1.

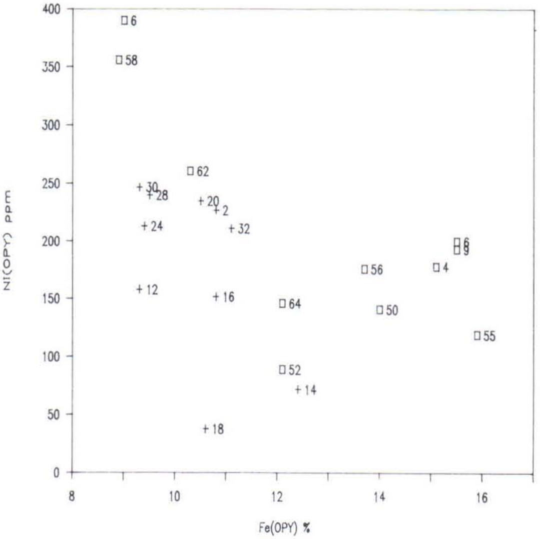

Fig. 39. Iron and nickel contents of orthopyroxene by intrusion. Square = Kotalahti-type targets, cross = Vammala-type targets. The location codes of the intrusions are given in Table 1.

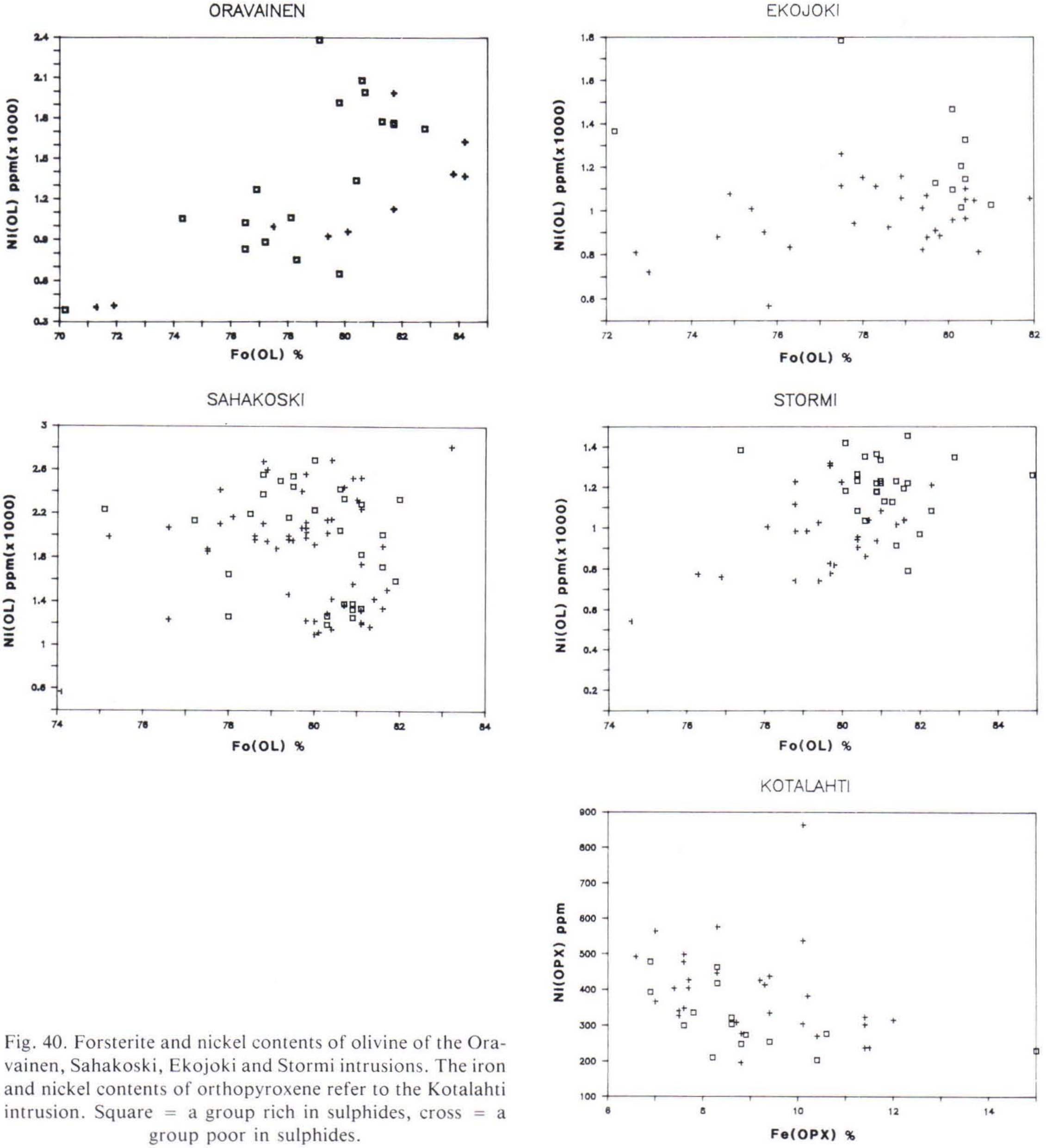

Fig. 40. Forsterite and nickel contents of olivine of the Oravainen, Sahakoski, Ekojoki and Stormi intrusions. The iron and nickel contents of orthopyroxene refer to the Kotalahti intrusion. Square = a group rich in sulphides, cross = a group poor in sulphides.

in Ni (Fig. 39). Moreover, the level of the nickel content is higher in the Kotalahti-type intrusions than in those of the Vammala type.

Although the concentration levels overlap in terms of ore potential and magma type, the difference in levels can still be established, as the highest average Ni contents in olivine and orthopyroxene are encountered in ore-potential intrusions and the lowest ones in barren intrusions. Intrusions rich in sulphides are Oravainen, Sahakoski, Hyvelä, Ekojoki, Stormi, Kylmäkoski, Laukunkangas and Kotalahti.

The composition of olivine reflects the basicity of the parent magma to a certain extent. In many intrusions the maximum forsterite content of olivine is about 84 %. The MgO/MgO + FeO ratio (X_{MgO}) of the parent magma was calculated from the formula of Roeder and Emslie (1970)

$$K_D = \frac{FeO(OL)}{MgO(OL)} \times \frac{MgO(L)}{FeO(L).}$$

The partition coefficient has a value of 0.33 (Bickle 1982, Duke 1986). According to the formula, olivine with 84 % forsterite is in equilibrium with a magma whose X_{Mg} is 0.63. This value is, however, rather low because basaltic magmas in equilibrium with the mantle have X_{Mg} between 0.68 and 0.72, corresponding to 87—89 % forsterite in olivine (Takahashi & Kushiro 1983).

If olivine crystals do not fractionate immediately after crystallization they are equilibrated with the residual melt and the forsterite content of olivine declines. This is likely to happen in an intrusion in which convection takes place, leading to a narrow compositional range for olivine (Arndt 1986). A few olivine crystals with 87 % forsterite (slide M 17666) have been met with in the Vammala intrusion. The highest forsterite content encountered in the Kotalahti intrusion was 89 % (slide M 7438). According to these contents the X_{Mg} of the magmas was 0.71. Data collected from the literature give 0.71 for the X_{Mg} of spinifex-textured komatiites with 15 % MgO. This figure is based on the following samples: 12 (Hanski 1979), BL32 (Nisbet *et al.* 1977), 10015, 10024 and 10064 (Francis 1985). The values obtained are tentative only, because Al_2O_3 and alkalies may have affected the activity of FeO and the composition of olivine (Takahashi 1978).

In this context the composition of olivines in ore-potential and barren groups was also examined (Fig. 40). The groups are the same as in chapter 11. The intrusions of Oravainen, Sahakoski and Stormi were selected as examples because they have different FeO to sulphide ratios. The Kotalahti material contained only a few olivine compositions, and hence the comparison was based on the orthopyroxenes. At Oravainen the forsterite content of olivine is slightly lower in ore-potential rocks than in barren rocks. At Stormi and Ekojoki the reverse holds, for there the forsterite content of olivine is higher in the ore-potential rocks. However, in the Kotalahti-type intrusions of Sahakoski and Kotalahti there is no difference in the composition of the silicates between the lithological groups.

13. DISCUSSION

1. Intrusion types

In international classifications all the Finnish Svecokarelidic intrusions hosting Ni-Cu sulphides are grouped into the same class. They belong to either orogenic (Naldrett 1979) or mafic and ultramafic intrusion types (Ross & Travis 1981). The intrusions defined by Ross and Travis are predominantly mafic, although they contain ultramafic rocks, too. These features fit the intrusions in the areas of Ahlainen, Kotalahti and Laukunkangas, but not those in the environment of Vammala (see Figs. 9, 11, 18 and 21). In the present study the classification was elaborated by subdividing the intrusions into the Kotalahti and Vammala types. No attention was paid to the classification of gabbro intrusions in this context.

In the lithological series of the Kotalahti type, the first intercumulus phase of olivine and orthopyroxene is clinopyroxene, which is later replaced by plagioclase. The rock types include peridotites, norites and gabbros. The proportion of mafic rocks is high in the intrusions, and the ultramafites are rich in orthopyroxene (Fig. 31).

In the Vammala-type lithological series clinopyroxene is the only intercumulus mineral of olivine and orthopyroxene, and the differentiation of the peridotites has advanced towards clinopyroxene-predominant pyroxenites (Fig. 30). The rock types met with are peridotites, olivine websterites and pyroxenites. The abundance of gabbroic differentiates is low, and they contain orthopyroxene, clinopyroxene and plagioclase.

The differences between the crystallization series may be ascribed to numerous factors effective at different times during the magmatic evolution, at either the crystallization, preintrusive or partial melting stages. It is not possible to evaluate all these factors here, but, however, in the following the whole magmatic evolution, starting with crystallization, is examined.

The conditions that prevail during crystallization affect the liquidus fields of the minerals, with the consequence that a parent magma may produce different crystallization series. The most conspicuous petrographic differences between the Kotalahti and Vammala types of rock are due to the proportions of orthopyroxene, clinopyroxene and plagioclase. The growth of the liquidus field of clinopyroxene in relation to the field of plagioclase may be attributed to 1) increase in pressure (Presnall *et al.* 1978), 2) increase in H_2O and alkali metal contents (Biggar 1983, Irvine 1979) or 3) increase in normative quartz (Biggar 1983). According to Kushiro (1975), the effect of P_2O_5 on the silicate melt is the reverse of that of alkalies. Therefore, the increase in P_2O_5 increases the volume of plagioclase.

However, none of the above options is fully consistent with the characteristics of the lithological types. First, the Vammala-type magmas crystallized, as we shall see later, at lower pressures than the Kotalahti-type magmas. Second, there are no clear differences in the alkali metal and H_2O contents. The P_2O_5 content is occasionally fairly high in the rocks of the Kotalahti type, but there is no systematic difference between the lithological types (Fig. 41).

The greater crystallization depth of the Kotalahti-type magmas promotes the crystallization of orthopyroxene relative to that of clinopyroxene (Arndt 1976, Green *et al.* 1975). According to Arndt, in komatiitic magma olivine is in equilibrium with orthopyroxene at pressures exceeding 15 kbar. However, in this context it is not possible to assess the crystallization depths of the magmas quantitatively.

A magma may become contaminated at a preintrusive stage as well as during crystallization, with the result that the crystallization order of the minerals may change. Campbell (1985) ascribed the high abundance of normative hypersthene in continental tholeiites relative to marine tholeiites to contamination. The marine tholeiites represent a more primary parent magma type and are characterized by a high clinopyroxene abundance. Contamination may have played a role in the evolution of the Kotalahti and Laukunkangas magmas, because these intrusions are located close to the Archaean craton in contrast to the intrusions of Hitura and Vammala which are farther away from the craton (Fig. 1).

On a larger scale, too, the intrusions resembling the Kotalahti-type are located in continental areas. Hence, all the intrusions in the Kola peninsula, except those of Petsamo, have similarities with the Kotalahti-type intrusions. The Kola peninsula is an Archaean continental area (Gorbunov *et al.* 1985). The Västerbotten intrusions, however, which resemble the Vammala type and are located in a marine environment, contain ultramafites and are rich in CaO relative to Al_2O_3 (Nilsson 1985).

The ultramafites of the present study show some similarities to the Canadian ultramafites in the Thompson belt and the Cape Smith zone (Peredery 1982). The Vammala-type intrusions resemble the Cape Smith ultramafites, in which differentiation proceeded towards the clinopyroxene field. In some places the differentiation of the intrusions did not advance beyond peridotites (Duke 1986). The intrusions in the Cape Smith zone and in the Vammala area are located in a Proterozoic geosynclinal basin (Francis & Hynes 1979). In contrast, the crystallization of the ultramafites in the Thompson belt was orthopyroxene-predominant, as was that of the Kotalahti-type intrusions, although in general the differentiation seldom advanced beyond peridotites. The lithological associations of the Thompson belt greenstones cannot be compared with any Svecokarelian environment (Peredery 1982).

The Kotalahti-type intrusions cannot, however, be placed in a continental environment, because they occur in geosynclinal basins that developed during the Svecokarelidic orogeny (Papunen & Vorma 1985). The Kotalahti-type magmatism encountered in the Ahlainen area is also outside the Archaean craton (Huhma 1987, Patchett & Kouvo 1986).

The implications of contamination for the magma types can best be examined in the present study with the aid of the trace element ratios. The lithological types do not differ in their ZrO_2/P_2O_5 ratios, which change readily as a result of contamination. Therefore none of the differences between the magma types can be ascribed to contamination (Fig. 41). Nor has contamination changed the mineral assemblage in the Oravainen intrusion, for, despite contamination, the differentiation proceeded in the clinopyroxene field.

At the preintrusive stage the differentiation of a mantle-derived magma may proceed in different ways, and it is to this stage that the internal compositional variations in the lithological series of the Kotalahti and Vammala types, but not the differences between the types, can be attributed (see the following chapter on the ore potential of the intrusions). The Kotalahti type should represent a Vammala-type differentiate, because the normative hypersthene increases in this direction. This is not possible, however, since, as the structural features suggest, the Vammala-type magmas crystallized close to the surface, whereas the Kotalahti-type magmas crystallized under plutonic conditions.

The best evidence for sub-surface emplacement at Vammala is the oxidation of the sulphides, the agglomeratic structures and the occurrence of a fine-grained cortlandite (Häkli *et al.* 1979). The orbicular peridotite of Kylmäkoski has also been interpreted as having formed close to the surface as a result of rapid crystallization (Papunen 1986a). It is also worth mentioning that the Västerbotten ultramafites that resemble the Vammala-type intrusions exhibit volcanic structures (Nilsson 1985).

The marked variation in Cr_2O_3 between the ultramafites of the Vammala intrusions can also be attributed to subsurface magma evolution (Fig. 35). Before pyroxene starts to crystallize in the most mafic rocks, Cr_2O_3 is bound only to chromite, whose occurrence is largely controlled by oxygen fugacity (Hill & Roeder 1974). The variation in oxygen fugacity may be partly due to water that entered the magma, because the amphibole of the cortlandites has been interpreted as primary (Mäkinen 1984).

Hence the difference between the Kotalahti and Vammala types is due not to factors related to magmatic evolution or crystallization but to primary features of the magmas, which were predominantly controlled by the P-T conditions under which they were formed, to volatiles and to the composition of the mantle matter.

Let us first consider the composition of the starting material, because the observations of Huhma (1986) on the heterogeneity of the mantle are compatible with regional variations in the composition of mafic intrusions. The average Al_2O_3 content is higher in the Joutsenmäki-Tolvaniemi and Parikkala intrusions in the eastern part of the Raahe-Ladoga belt, and in the Ahokkala, Toivakka and Kangasniemi intrusions than in the other mafic intrusions (Fig. 34). The high Al_2O_3 values in the ultramafites in the environment of Kotalahti and Laukunkangas obviously derive from the mantle, as implied by the low ε_{Nd} in the Laukunkangas norites (Huhma op.

cit.). Accordingly, the anomalously high P_2O_5 values at Laukunkangas and Hälvälä are primary features, as are the high TiO_2 values at Parikkala (Appendix 2, Fig. 33).

The mantle was not, however, very heterogeneous, as the ZrO_2/P_2O_5 ratios do not differ between areas or magma types (Fig. 41). The ratios were calculated from the peridotitic rocks with only olivine and orthopyroxene as cumulus minerals. The absolute contents also show considerable overlap, although occasionally the Kotalahti-type peridotites are rich in incompatible elements. This feature is similar to that of the anomalously high P_2O_5 values at Laukunkangas and Hälvälä, which are not depicted in Fig. 41. The values in Fig. 41 are, however, only indicative, because it was not possible to assess the degree of fractionation of the cumulates relative to the parent magmas.

If the Kotalahti and Vammala-type magmas were products of partial melting of equal degree then the starting material of the Kotalahti-type parent magma was slightly richer in incompatible elements than was that of the Vammala-type magma.

Changes in temperature can also result in magmas differing in composition. Magmas generated at low temperature are rich in incompatible elements because the degree of partial melting is low. This feature is characteristic of the Kotalahti-type magmas, as is the high La/Yb ratio (5.9) in the Kotalahti peridotites (Papunen & Koskinen 1985). The Stormi peridotites have a La/Yb ratio of 1.7 (Mäkinen 1984). The CaO/Al_2O_3 ratio decreases when the degree of partial melting decreases (Jacques & Green 1980, Nisbet *et al.* 1979).

Despite the differences in magma types the distribution of forsterite content in olivine is similar in the Kotalahti and Vammala-type intrusions. However, it is difficult to assess how primitive the parent magmas were, because the composition of the cumulus olivine was affected by several secondary factors. Thus, for example, the forsterite content in the Ekojoki olivine does not differ from that in the rest of the material (Fig. 38), even though the lanthanide distribution in the peridotites is almost chondritic (Mäkinen 1984).

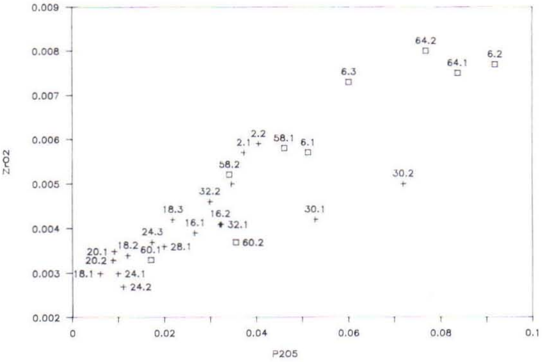

Fig. 41. The P_2O_5 to ZrO_2 ratios of the lithological groups. Square = Kotalahti type, cross = Vammala type. The location codes of the groups are given in Table 1.

The emplacement of the Vammala ultramafites close to the surface might be due to a geothermal gradient steeper than that at, say, Ahlainen. In that case the degree of partial melting would have varied areally, resulting in parent magmas differing in composition. However, in the Kynsikangas zone the magma type changes abruptly. Therefore, it is unlikely that only the thermal conditions would have changed laterally at such a high rate. The intrusions of the Kotalahti type occur west of the Kynsikangas, and those of the Vammala type east of it.

The depth at which a magma crystallizes depends on tectonic conditions, and it is likely that differences between magma types are due to pressure rather than temperature. The cyclicity of the mafic-ultramafic magmatism in the Raahe-Ladoga belt might also be ascribed to tectonic control (Tontti *et al.* 1979). Under orogenic conditions, pressure may change more easily than the other parameters, and it may be the cause of the sudden compositional variations in magmas. It should also be kept in mind that the generation of magmas dealt with in this context was due to tectonic rather than intense thermal activity.

It is true, though, that sudden changes do take place in the degree of partial melting, but then they are related to tectonic conditions. For example, at the mid-oceanic ridges the degree of partial melting suddenly declines towards the transform fault because the spreading axis terminates at the transform fault, beyond which there is a cold plate (Langmuir & Bender 1984).

The lithological series of Koirusvesi, which contains peridotites, norites and pyroxenites with abundant clinopyroxene, is also indicative of variation in pressure. The norites are poor in incompatible elements and are thus not the products of low-degree partial melting.

According to Thompson (1984), the normative diopside in the forming magma is fairly high in relation to normative hypersthene up to c. 20 kbar. At higher pressures, however, normative diopside declines and normative hypersthene increases. This interpretation implies that the Kotalahti-type magmas were generated at higher pressures than the Vammala-type magmas.

Note, too, that the water present at the generation stage of a magma increases the abundance of normative hypersthene in magma (Burnham 1979). The high normative hypersthene in the Kotalahti type, however, is not due to water, because the intrusion contains only a little primary amphibole. It can therefore be deduced that the magmas were not generated directly through the action of the Benioff zone, because in that zone the generation of a magma is caused mainly by the presence of water (Wyllie 1981).

The variation in pressure in the Raahe-Ladoga and Ahlainen-Kylmäkoski belts was probably due to the splitting of the lithosphere into blocks varying in thickness. The Kotalahti-type magmas were generated in a thicker block or in its margins, whereas the Vammala-type magmas were produced in a thinner block.

To sum up, the heterogeneity of the mantle contributed to the differences in magma types. Partial melting at different pressures also resulted in magmas of different composition. It is possible, too, that the degree of partial melting varied, but that cannot be established from the present material.

2. Ore potential

The fact that the ore potential of the mafic and ultramafic lithological assemblages manifests itself not only in sulphides but also in elements incorporated in silicates is a reflection of complex relationships. In order to assess ore potential one should be able to recognize the causal relations in the elemental changes; however, this was not always possible with the material available.

The factors affecting the ore potential of the ultramafic intrusions were always very similar, as the SiO_2, TiO_2, Al_2O_3, FeO and P_2O_5 contents vary regularly along with the variation in sulphide content (Appendix 3). At Oravainen and Hitura the internal SiO_2 and FeO contents of the intrusions are exceptional. Nevertheless, the total contents in the intrusions follow the general trend, i.e. the rocks rich in sulphides are rich in SiO_2 and poor in FeO (Figs. 32, 36). The Hitura intrusion differs from the Svecokarelidic ultramafites in other respects, too, for the concentration profile of its platinum group elements is similar to that of the komatiites (Papunen 1986b). Despite the dissimilarity in the modes of differentiation in the Vammala and Kotalahti-type intrusions, the ore potential manifests itself in their most mafic members in a similar manner.

However, the mode of mineralization varies in accordance with the basicity of the magma, the element to sulphide ratios of the Laukunkangas and Joutsenmäki-Tolvaniemi intrusions being different from those of the ultramafic intrusions.

According to several previous studies (Clark 1980, Häkli *et al.* 1978, Naldrett 1981), ore potential has a positive correlation with SiO_2 content and a negative correlation with FeO content. In general, the high SiO_2 content is due to contamination, although this does not apply to all the targets studied. The FeO content is probably a primary feature of the magma (Langmuir & Hanson 1980). In Australian komatiites other factors, too, are related to ore potential, and some of them are similar to those encountered in the targets of the present study. According to McQueen (1981), mineralized komatiites are poorer in TiO_2 and Al_2O_3 than are other lava flows.

The ore potential of an intrusion generally changes within the rocks of one and the same differentiation series, because the variation in the lithophile elements is gapless. The same changes are also encountered in the internal magma pulses of an intrusion and between intrusions. Therefore, the ore potential as a whole can only be considered on the basis of the regularities observed in the crystallization differentiation. In the following we shall examine the factors that affect the differentiation of an intrusion internally and externally, because both factors control the behaviour of the magma.

The contamination of a magma or changes in oxygen fugacity are generally ascribed to external factors. The variation in SiO_2 implies contamination, but the reverse variations in Al_2O_3 and P_2O_5 are not consistent with the concept of contamination. If there had been contamination, the ore-potential rocks would have been rich in Al_2O_3 and P_2O_5 (Watson 1976).

Contamination has clearly altered the composition of the Oravainen peridotites, as shown by their high SiO_2 and alkali contents. However, the results indicate that contamination and mineralization were not concomitant, because the alkali contents reflecting contamination do not vary in relation to the sulphide content. Nor are the SiO_2 contents in rocks with abundant sulphides clearly higher.

In the Hitura intrusion the variation in SiO_2 relative to sulphides is similar to that in the Oravainen intrusion. Sulphides were therefore formed in the same way in both intrusions. The margins of the Hitura intrusion are contaminated to some extent (Isohanni *et al.* 1985), but not even at Hitura is the mineralization directly associated with contamination, for the SiO_2 content varies inversely with the sulphide content.

In places mineralization was accompanied by high oxygen fugacity, as shown by the abundant Cr_2O_3 in the ore-potential rocks of Hitura and Oravainen. In the Kotalahti intrusion the variation in Cr_2O_3 relative to sulphides is ascribed to pyroxenes, because the chromite content of the rocks is very low. In the intrusions of Hitura and Oravainen the variation in Cr_2O_3 is due to chromite. Similar cases, caused by increased oxygen fugacity (Woolrich *et al.* 1981), are known from the Ni-Cu ores associated with komatiites. The increase in oxygen fugacity promotes the formation of sulphide ore, because it widens the liquid immiscibility gap between the sulphide and silicate phases (MacLean 1969). The chromium dissolved in sulphides might also have affected the Cr_2O_3 contents (Ewers *et al.* 1976), but this cannot be verified in the present study. As shown by these examples, a high Cr_2O_3 content is not necessarily an indicator of ore potential; for example, in the Hoipola intrusion, the Cr_2O_3 and sulphide contents have a negative correlation (Fig. 7), and at Posionlahti, the rocks poorest in sulphides are the richest in chromite.

Nevertheless, the intrusions of Hoipola and Posionlahti cannot be correlated with those of Hitura and Oravainen, for at Hoipola and Posionlahti the variation in Cr_2O_3 is due to preintrusive events. In both intrusions the highest Cr_2O_3 contents are met with in the second magma injection. The behaviour of Cr_2O_3 relative to sulphides in a system within an intrusion may be different from that in a system consisting of a magma chamber and an intrusion.

No other external factors affecting the magma were assessed, and it can be concluded that the mineralization processes in the intrusions studied were not associated with contamination. In places there are signs indicating elevated oxygen fugacity but the results are ambiguous.

The conclusion concerning contamination is in harmony with observations from Precambrian ultramafites. According to Foose (1982), ore formation in Archaean and Lower-Middle Proterozoic ultramafites is mostly associated with differentiation of the magma. Only in younger intrusions, such as continental layered intrusions, is mineralization associated with contamination.

In the following we shall examine the magma system from within. The dependence of the variations in several elements (SiO_2, TiO_2, Al_2O_3, FeO, P_2O_5 and ZrO_2) on the sulphide content suggests that they are not due to external factors but to reactions associated with sulphide formation.

Sulphides are formed in the ultramafic magma mainly at the initial stages of crystallization, with olivine and orthopyroxene as liquidus phases. The variations in element contents must, therefore, be due to fractionation of the mafic components or sulphides.

The fractionation of olivine and orthopyroxene increases the abundances of TiO_2, Al_2O_3, P_2O_5 and ZrO_2 in the residual melt, because the partition coefficients between crystals and melt are low. Hence, the barren rocks should represent phases crystallized from residual magma. This is corroborated by the low forsterite contents in the olivines of the barren rocks in the Stormi and Ekojoki intrusions (Fig. 40). However, both groups have the same compositional range for MgO, which might be attributed to the accumulation of olivine in a residue rich in incompatible elements (Appendix 3).

Apart from mafic silicates, sulphides also fractionate from the magma. The fractionating sulphides scavenge transition elements (Fe, Co, Ni and Cu), because their partition coefficients between the sulphide and silicate phases are high (Rajamani & Naldrett 1978). The fixation of transition elements to sulphides reduces the density of the residual magma, changing its ability to fractionate. The reduced density of the magma improves the fractionation of the cumulus crystals, and the contents of the incompatible elements in cumulates remain low (Duke & Naldrett 1978, Maaloe 1976). The outcome is a compositional difference between the sulphide-bearing cumulates and those free of sulphides.

The variation in SiO_2 relative to the sulphides cannot, however, be explained by the above models, for the fractionation of olivine leads to enrichment of the residual melt in SiO_2. The more intense the fractionation, the more rapidly SiO_2 increases in the residue owing to the subdued peritectic reaction between olivine and the residual magma (Morse 1980).

The slight variation in sulphide content does not result in marked differences in the texture of the crystallizing silicates. Nor is there any difference in the abundances of the minerals. However, the high sulphide content is associated with the high abundance of olivine relative to that of the other silicates, and the net-textured ores are composed of olivine and sulphides only. The compositional variation in the lithological series is similar to that in olivine cumulates. However, euhedral pyroxene crystals often occur on the boundary between the sulphide and silicate phases, raising the SiO_2 content in the cumulate. The intergrowth textures of orthopyroxene and sulphides have the same effect (cf. Ripley & Alawi 1986, Tyson & Chang 1984), although they are only of minor importance. The growth of pyroxene around olivine may be due to the incomplete separation of sulphides and silicates in liquation. It is possible that some of the silicate polymers do not separate from the sulphides to form cumulus crystals and increase the SiO_2 content in cumulate until after the cumulus stage.

The variation in most of the incompatible elements (TiO_2, Al_2O_3, SrO, P_2O_5 and ZrO_2) relative to sulphides is caused by the fractionation of mafic minerals and sulphides, but this cannot be applied to SiO_2 and FeO. Some models were outlined above for the behaviour of SiO_2. The behaviour of FeO, however, is more complicated, because it has an affinity for sulphide, silicate and oxide phases. The behaviour of FeO cannot be explained by the fractionation of sulphides, because in that case the FeO in barren residue should decline. On the other hand, the sulphides may have been equilibrated with the cumulates, with the consequence that part of the iron of the ore-potential cumulates entered into sulphides.

The relative enrichment of residual magma in

SiO_2 and FeO is one of the fundamental issues in magma petrology. Experimental studies have demonstrated that low oxygen fugacity promotes the enrichment of the residual magma in FeO relative to SiO_2, as the crystallization rate of the oxides containing FeO is very low at initial stage of the differentiation. This is typical of tholeiitic differentiation. In contrast, high oxygen fugacity promotes the crystallization and fractionation of oxides, resulting in the loss of FeO in residual melt in relation to SiO_2. This differentiation trend is characteristic of the calc-alkali rock series (Kushiro 1979, Morse 1980).

In the intrusions of Oravainen and Hitura, chromite crystallized together with sulphides. What is more, the variation in SiO_2 and FeO contents is the reverse of that in the other intrusions, suggesting that the mutual behaviour of SiO_2 and FeO was controlled by oxygen fugacity. However, this concept is not supported by the composition of olivine, because in the Oravainen intrusion the forsterite content decreases slightly as the ore potential and chromite content increase. The forsterite content in olivine should increase parallel to the increase in oxygen fugacity (Mysen 1975). The situation is complicated, however, because the contents were calculated from the cumulates, and the sulphides buffer the oxygen fugacity. Nevertheless, the Oravainen intrusion shows that the FeO content in the cumulate is controlled by the compositions of the silicates (Fig. 40). The variation in FeO contents cannot be explained quantitatively by the cumulation of chromite.

In the Stormi and Ekojoki intrusions the total iron content is mainly controlled by the compositions of the silicates, for the olivine in the barren rocks is poorer in forsterite than the olivine in the ore-potential rocks (Fig. 40). Therefore, the olivine in the barren rocks crystallized from magma with a low X_{Mg}.

In general, the variations in the alkali metal contents relative to the sulphides are not like those of the other incompatible elements; only in the Kylmäkoski intrusion did all the incompatible elements behave in the same way. In some sulphide factors the alkali metals have the opposite loadings to those for sulphides (12*4, 24*2 and 28*2) (Appendix 1). At the subsolidus stage the alkali metals are distinctly more mobile than the other elements, with the consequence that the original variation in composition may be partly camouflaged by later changes.

Various ore-potential models were compared with the geological background by considering the location of the ore-potential and barren rocks within the intrusion. The Stormi intrusion, in which the ore-potential peridotites and barren cortlandites occur in different layers, is the best example of this. It shows that the barren rocks are late differentiates, as assumed in the above fractionation model. The model is consistent with the compositional variations, because the Stormi cortlandites are poor in SiO_2 and rich in TiO_2 (Figs. 32, 33). The loadings on factor 2 calculated from the Stormi peridotites also follow the trend of the fractionation model (Fig. 10b). The composition gradient described by the model was formed between the rocks associated with the Korvalampi orebody and those southwest of the orebody. The same applies to factor 2, which is in group 4 in Table 3 and refers to the differentiation of the peridotites in the Haavisto intrusion. At Haavisto the abundance of sulphides is highest at the base and in the eastern part of the intrusion.

The almost identical La/Yb ratios in the cortlandites and peridotites are also in harmony with the fractionation model. To attribute the high TiO_2 content to the variation in the degree of partial melting requires the La/Yb ratios in cortlandites to be higher than in peridotites (Mäkinen 1984).

The Posionlahti intrusion, in which the rocks poorest in sulphides are products of the second magma injection, serves as another example. At Posionlahti the content ratios of the groups correspond fairly well to the variation shown by the ore potential (Figs. 32—36).

Nisbet and Chinner (1981) attributed the formation of sequential lava layers, of which the first one is rich in sulphides, to fractional crystallization. The second layer is more silicic and has a lower abundance of sulphides and more TiO_2 than the first one. According to Groves (1981), the ore-potential rocks in lava piles in western Australia are often the lowest in stratigraphy.

Inter-intrusional and intra-intrusional magmatic evolutions exhibit certain similarities, as the intrusions rich in Ni-Cu sulphides are poor in TiO_2, Al_2O_3 and FeO and rich in SiO_2 (Figs. 32—36); such intrusions are Oravainen, Stormi, Kylmäkoski, Kotalahti and Hitura. This is natural, because the adjacent intrusions presumably derive from similar parent magmas, and crystallization proceeded in the same way both before and after emplacement. Therefore, the barren intrusions represent late differentiates of the magma chamber, formed when the sulphides and mafic minerals fractionated. The magma chamber must have fractionated close to the ground surface, otherwise the inter-intrusional and intra-intrusional element variations would differ from each other. The increase in pressure alters the liquidus fields of the minerals, with the consequence that the minerals fractionate in proportions different from those encountered under surficial conditions.

The low nickel contents of olivine and orthopyroxene in the barren intrusions can also be attributed to the fractionation of olivine and orthopyroxene before the final emplacement (Figs. 38, 39). However, it is possible that in-situ fractionation of the sulphides at the final crystallization stage lowers the nickel content in silicates, and hence unambiguous conclusions on the ore potential cannot be drawn from the silicate compositions (Duke 1979). Nevertheless, the present material suggests that the nickel content has a moderate positive correlation with the ore potential of an intrusion. The final compositions attained by the silicates in the mineralization event are largely controlled by the silicate to sulphide mass ratio and the mode of fractionation of the sulphides (Naldrett *et al.* 1979). Of course, the original nickel content in magma is one of the factors (Häkli 1963). The nickel content of the silicates may also change at the subsolidus stage. The results of the present study suggest that the amount of sulphides was not always sufficient to extract nickel from the silicates or that the sulphides did not attain equilibrium with the whole silicate fraction.

The fractionation model can also be applied to some of the areal features of the ore potential, which decreases from Stormi towards the intrusions of Sittamäki and Murto. This is probably due to the variation in temperature, the thermal gradient being steeper in the middle of the tension zone than in its environment. If it is assumed that the bulk of the ultramafic parent magma was generated at this site, the magma that advanced in the middle of the tension zone did so in the warmest environment. On the flanks of the tension zone the thermal gradient was gentle, cooling the effusive magma rapidly. At the same time the fractionation probability of the magma increased and its ore potential decreased.

In mafic intrusions the elemental variations are the reverse of those in ultramafites, and the mineralization process is different from that in ultramafic intrusions. The best example of the mineralization process of mafic rocks is given by the Laukunkangas norites, which underwent intense mineralization. The high SiO_2, Al_2O_3, CaO, SrO and N_2O values of the barren rocks in the Laukunkangas intrusion can be attributed to the accumulation of plagioclase (Appendix 3). Fractionation probably took place, as the density of the plagioclase is markedly lower than that of the sulphides and mafic minerals. The total contents of the Laukunkangas intrusion are unusual, for the rocks rich in sulphides are very poor in SiO_2 (Fig. 32, case 55*1).

The formation of sulphides was modest in the Joutsenmäki-Tolvaniemi intrusion, and hence, the elemental variations are small relative to the sulphide content. Sulphide mineralization in the Joutsenmäki-Tolvaniemi intrusion was associated with fractionation of the felsic and mafic minerals (Appendix 3), and the sulphides accumulated together with the mafic minerals.

The ore potential was also assessed with the aid of normative compositions. First, high normative hypersthene increases the ore potential of Kotalahti-type intrusions (Haughton *et al.* 1974). Second, the behaviour of nickel in Vammala-type magmas differed from that in Kotalahti-type magmas, as shown by the variation in normative plagioclase and diopside.

The nickel contents in silicates (Figs. 38, 39) indicate that geochemical equilibrium was not the same in the Kotalahti and Vammala-type rocks. According to Rajamani and Naldrett (1978), nickel tends to enter the phases with the strongest fractionation when the contents of alkali metals and Al_2O_3 increase. Alumina and alkali metals also increase the FeO activity in silicate melt, reducing the solubility of the sulphide phase and increasing the ore potential (Roeder 1974). The negative correlation between the sulphides and Al_2O_3 observed in the present study contradicts the results of Roeder (op. cit.). The discrepancy is, however, ostensible, because the observations of the present study were made on cumulates, whereas those of Roeder refer to the equilibrium stage.

According to the results of Roeder the formation of an immiscible sulphide phase during differentiation is more likely in Kotalahti-type intrusions than in those of the Vammala type. In Kotalahti-type rock series the proportion of Al_2O_3 increases rapidly, as shown by the high normative plagioclase. As a consequence the segregation of sulphides is effective, and sulphides occur in both peridotites and norites. The segregation is also capable of explaining the breccia ores associated with the rocks rich in quartz and feldspar in the Kotalahti intrusion, (Papunen 1970).

The effect of CaO on ore potential is the reverse of that of Al_2O_3, as it increases the solubility of the sulphides in magma (Haughton *et al.* 1974, Shima & Naldrett 1975). In the Vammala-type magma the high CaO content raises the solubility of the sulphides and reduces the likelihood of Ni-Cu ore forming during differentiation. Sulphur dissolved in magma eventually segregates as a separate phase, and the ore potential is controlled not only by CaO and Al_2O_3 but also by many other factors. However, in some Vammala-type intrusions sulphides occur only in the most mafic differentiates. Thus, in the intrusions of Oravainen and Kylmäkoski, for example, sulphide mineralization was strongest during the crystallization of the peridotites, whereas hardly any sulphides were formed when the pyroxenites crystallized.

The conclusions about the ore potential of the rock types are similar to those drawn by Teil (1976). With the aid of correspondence analysis, Teil compared the ore potentials of 186 mafic and ultramafic intrusions. According to him, peridotites and norites are ore-potential, whereas pyroxenites are barren.

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Appendix 1. Factor loadings by factor group. The factor group code is at the top and the location code and the order of the factor underneath it. The location codes are explained in Table 1. The factor loadings calculated from the total data on Stormi, Makkola and Liakka are given under the codes of 26, 53 and 71, respectively. The percentage of explanation of the factors is at the bottom. The values of the factors are the opposite to the real ones if the ordinal of a factor is provided with the code X. The loadings for the variables SiO_2—ZrO_2 were calculated from the XRF data and those for Cu—Co from the AAS data. At the end of the table there are factor loadings provided with the code XRF, which were calculated from the XRF data only.

	1	1	1	1	1	1	1	1	1
	10*3	18*1	20*1	24*1	26*1	32*1	58*1	66*2	12*2
SiO_2	.	0.55	.	0.49	.	.	.	0.40	.
TiO_2	0.60	0.90	0.77	0.60	0.89	0.84	0.79	0.46	0.95
Al_2O_3	0.47	0.92	0.82	0.79	0.84	0.88	0.77	0.71	0.91
Cr_2O_3	.	—0.59	.	.	—0.47	.	—0.57	.	—0.40
FeO	.	—0.37	.	.	.	.	.	.	.
MnO	.	.	.	.	.	.	—0.28	.	.
MgO	—0.26	—0.68	—0.33	—0.54	—0.63	—0.52	—0.57	—0.46	.
CaO	.	0.45	.	.	0.54	.	.	.	.
SrO	0.94	0.64	0.87	0.60	0.87	0.86	0.90	0.57	0.58
BaO	.	.	.	0.67	.	.	0.88	0.68	.
Na_2O	0.83	0.83	0.82	0.71	0.89	0.84	0.91	0.45	0.85
K_2O	.	0.82	0.27	0.84	.	.	0.29	0.86	.
P_2O_5	0.29	0.68	0.70	0.81	0.81	0.65	0.88	0.73	.
ZrO_2	0.66	0.84	0.81	0.80	0.91	0.76	0.94	0.76	.
Cu	.	.	.	.	.	.	.	.	.
Zn	.	—0.27	.	.	—0.27	.	—0.43	.	.
Ni	.	—0.40	.	.	—0.20	.	.	.	.
Co	.	—0.39	.	.	—0.36	—0.27	—0.25	.	.
S	0.35	.	.	.	.	.	.	.	0.62
%	10	59	40	38	45	34	43	18	24

	1	2	2	2	2	2	2	2	3
	14*1	12*1	18*3	20*2	32*2	58*3	14*4	30*1	10*1
SiO_2	0.79	—0,95	—0.59	—0.89	—0.78	—0.56	—0.43	—0.58	0.82
TiO_2	0.39	.	.	.	.	—0.32	.	—0.65	0.46
Al_2O_3	0.90	.	.	.	.	—0.37	.	.	0.55
Cr_2O_3	—0.52	.	0.31	—0.69	—0.49	.	—0.62	—0.38	.
FeO	—0.30	0.88	0.69	0.95	0.91	0.83	0.84	0.63	—0.76
MnO	.	0.57	0.86	0.75	0.67	0.69	.	.	.
MgO	—0.86	0.85	0.49	0.72	0.74	0.65	.	0.74	—0.79
CaO	0.64	—0.81	—0.60	—0.71	—0.85	—0.88	.	—0.98	0.64
SrO	0.87	.	.	.	.	.	.	.	.
BaO	0.70	0.25	.	.	.	.	.	.	.
Na_2O	0.88	.	.	.	.	.	.	.	0.40
K_2O	0.95	.	—0.27	.	.	.	.	.	0.26
P_2O_5	0.95	.	—0.43	.	.	.	.	.	0.25
ZrO_2	0.94	.	—0.29	.	.	.	.	—0.26	.
Cu	.	0.31	.	.	.	.	.	.	0.28
Zn	—0.86	.	.	.	0.62	.	.	0.91	—0.37
Ni	.	0.31	0.36	.	.	.	.	0.38	—0.31
Co	—0.67	.	0.40	.	.	.	.	0.28	—0.26
S	.	—0.35	.	.	—0.26	.	—0.65	.	.
%	55	30	7	21	21	12	5	45	37

	3 02*1 *****	3 16*1	3 24*3	3 28*1	3 66*1	4 02*2	4 04*2	4 06*3	4 10*4
SiO_2	0.87	0.87	0.77	0.89	0.63	—0.28	.	.	.
TiO_2	0.71	0.83	0.45	0.84	0.79	.	.	.	.
Al_2O_3	0.39	0.84	0.32	0.81	0.65	.	.	.	.
Cr_2O_3	—0.79	.	0.25	—0.66	.	0.41	.	.	.
FeO	—0.60	—0.90	—0.80	—0.78	.	0.38	.	.	.
MnO	.	—0.38	—0.67	—0.51	0.67	0.56	.	.	.
MgO	—0.96	—0.94	—0.68	—0.93	—0.83	.	.	.	.
CaO	0.80	0.91	0.84	0.89	0.91	.	.	.	.
SrO	—0.27	0.27	0.30	.	0.57	.	.	.	.
BaO	.	.	.	.	0.26	.	.	.	.
Na_2O	0.38	0.85	0.45	0.69	0.74	.	.	.	.
K_2O	.	0.31	.	0.61	.	.	.	.	.
P_2O_5	.	.	.	0.35	.	.	.	.	.
ZrO_2	.	0.26	.	0.52	0.38	.	.	.	0.37
Cu	.	.	.	.	.	0.90	0.94	0.88	0.76
Zn	.	—0.73	.	—0.30	.	.	0.35	.	.
Ni	—0.27	—0.65	.	.	.	0.90	0.92	0.82	0.88
Co	—0.27	—0.80	.	—0.50	.	0.92	0.97	0.41	.
S	.	.	.	.	.	0.93	0.96	0.83	0.71
%	34	48	10	44	39	26	22	9	9

	4 12*4	4 14*2	4 16*2	4 18*4	4 20*3	4 24*2	4 28*2	4 30*4	4 32*3
SiO_2	.	.	.	.	.	.	.	.	.
TiO_2	.	.	.	.	.	—0.42	—0.33	.	.
Al_2O_3	.	.	.	.	.	—0.39	—0.41	.	.
Cr_2O_3	.	—0.36	—0.57	.	.	.	.	.	.
FeO	.	.	.	.	.	—0.38	—0.36	.	.
MnO	.	.	0.33	.	.	.	.	.	.
MgO	.	.	.	.	0.28	0.33	.	.	.
CaO	—0.32	—0.34	.	.	—0.25	.	.	.	.
SrO	.	.	.	.	.	—0.47	.	.	.
BaO	.	.	.	.	0.25	0.27	.	.	.
Na_2O	.	.	.	.	.	—0.30	—0.36	.	.
K_2O	0.31	.	.	.	.	.	.	.	.
P_2O_5	.	.	.	.	.	.	—0.48	.	—0.26
ZrO_2	.	.	.	.	.	.	—0.25	.	.
Cu	0.54	0.90	0.94	0.76	0.91	0.77	0.92	0.80	0.90
Zn	0.45	.	.	.	.	.	.	.	.
Ni	0.88	0.90	0.64	0.69	0.98	0.87	0.94	0.62	0.94
Co	0.87	0.52	0.49	0.65	0.90	0.90	0.77	0.27	0.81
S	0.26	0.59	0.86	0.90	0.97	0.95	0.71	0.89	0.86
%	9	16	15	6	14	16	19	8	11

	4 34*4	4 44*4	4 46*2	4 48*2	4 50*2	4 52*2	4 54*2	4 56*2	4 58*2
SiO_2	.	.	.	.	.	.	—0.44	.	.
TiO_2	0.27	.	.	.	.	.	.	.	.
Al_2O_3	.	.	.	.	.	.	—0.29	.	—0.28
Cr_2O_3	.	.	.	0.68	0.30	.	.	.	.
FeO	0.30	.	.	.	.	.	.	.	—0.28
MnO	.	.	.	0.33	0.37	.	.	.	.
MgO	.	.	.	0.47	0.25	.	0.38	.	.
CaO	.	.	.	.	.	.	.	.	.
SrO	.	.	.	—0.28	.	.	.	.	.
BaO	.	—0.33	.	.	.	.	.	.	.
Na_2O	.	.	.	.	.	.	.	.	.
K_2O	—0.29	—0.36	.	—0.27	.	.	.	.	.
P_2O_5	.	.	.	.	.	.	.	.	.
ZrO_2	.	.	.	—0.39	.	.	.	.	.
Cu	0.66	0.79	0.88	0.95	0.81	0.89	0.84	0.62	0.80
Zn	.	.	0.55	.	.	.	0.64	.	.
Ni	0.30	0.59	0.81	0.83	0.78	0.94	0.83	0.40	0.94
Co	0.67	0.75	0.91	0.92	0.89	0.96	0.83	0.62	0.90
S	0.74	0.81	0.87	0.90	0.81	0.96	0.87	0.91	0.93
%	8	7	18	22	17	18	22	6	21

	4 64*2	4 66*3	4 74*3	4 70*4	4 72*4	4 04*4	4 06*4	4 38*1	4 40*3
SiO_2	.	.	.	.	.	.	.	—0.80	—0.87
TiO_2	0.29	.	—0.32	0.34	.	0.81	0.25	0.66	0.74
Al_2O_3	.	.	.	.	.	—0.26	.	.	.
Cr_2O_3	.	0.57	—0.31	—0.61	.	.	.	—0.28	.
FeO	.	.	.	.	.	0.65	0.61	0.90	0.72
MnO	0.28	.	.	.	.	0.65	0.91	0.84	.
MgO	.	.	0.42	—0.43	.	.	.	.	.
CaO	.	.	.	0.48	.	.	.	.	.
SrO	.	.	.	.	0.78	.	—0.27	.	.
BaO	.	0.37	—0.25	.	.	.	.	0.31	.
Na_2O	.	.	.	.	.	.	.	.	—0.25
K_2O	.	.	.	.	.	.	.	—0.33	.
P_2O_5	.	.	.	.	.	0.60	.	.	0.56
ZrO_2	.	.	.	.	.	.	—0.32	.	.
Cu	0.92	.	0.79	0.79	0.77	.	.	.	.
Zn	.	.	0.61	.	.	.	.	.	.
Ni	0.84	0.96	0.91	.	.	.	.	—0.30	.
Co	0.34	0.95	0.89	.	.	.	.	.	0.67
S	0.84	0.94	.	0.79	0.55	.	.	.	.
%	14	13	14	7	8	9	8	27	14

	5	5	5	5	5	5	5	5	5
	46*4	48*4	52*3	68*3	28*3	30*3	36*3	40*4	42*2
SiO_2	—0.49	.	—0.79	—0.66	.	—0.66	—0.64	.	—0.33
TiO_2	0.60	0.87	0.27	0.56	.	0.25	0.87	.	0.64
Al_2O_3	—0.39	—0.30	.	.	.	—0.54	.	—0.49	—0.68
Cr_2O_3	.	—0.26	—0.26	.	.	.	.	.	.
FeO	0.92	0.26	0.86	0.93	0.39	0.67	0.63	0.58	0.91
MnO	0.84	0.36	0.76	0.63	0.61	0.92	0.38	0.87	0.91
MgO	.	.	.	.	.	0.48	.	.	.
CaO	.	.	.	.	.	.	0.25	.	.
SrO	.	—0.31	—0.38	.	—0.26	.	0.51	—0.81	—0.66
BaO	.	0.31	—0.25	.	0.82	.	0.36	.	.
Na_2O	.	.	—0.32	.	.	—0.75	.	.	—0.53
K_2O	.	.	.	—0.28	0.27	—0.49	.	.	.
P_2O_5	0.51	0.91	.	0.37	.	—0.44	0.90	.	0.32
ZrO_2	.	.	—0.46	.	.	.	0.27	—0.53	.
Cu	.	.	.	.	.	.	.	0.26	.
Zn	.	.	.	.	—0.75	.	.	.	0.29
Ni	.	—0.25	.	.	.	.	.	—0.39	.
Co	.	.	.	0.43	.	0.31	.	.	.
S	.	.	.	.	—0.46	.	.	.	.
%	11	7	14	12	10	13	17	9	15

	5	5	6	6	6	6	6	6	6
	44*3	72*3	30*2	34*2	36*2	40*2	42*3	46*1	38*3
SiO_2	—0.81	.	—0.33	.	.	.	.	.	.
TiO_2	0.72	0.33	—0.43	—0.36	.	.	.	—0.66	—0.27
Al_2O_3	.	—0.86	—0.64	—0.88	—0.81	—0.79	—0.43	—0.48	.
Cr_2O_3	—0.25	.	0.86	0.82	0.91	0.91	0.66	0.84	0.29
FeO	0.83	0.74	0.27	.	.	.	.	.	.
MnO	0.41	0.89	.	.	.	.	.	.	.
MgO	.	.	0.34	0.73	0.89	0.89	0.70	0.93	0.47
CaO	.	—0.37	.	0.43	0.30	0.63	.	.	0.43
SrO	.	—0.28	.	—0.25	.	.	.	.	.
BaO	.	.	.	.	.	.	.	—0.35	.
Na_2O	.	.	—0.37	—0.58	—0.25	—0.69	—0.38	—0.72	—0.36
K_2O	.	.	—0.57	.	.	.	.	.	.
P_2O_5	0.34	.	.	.	.	.	—0.25	—0.54	.
ZrO_2	.	.	—0.61	.	.	.	.	—0.39	.
Cu	.	0.28	0.42	0.33	.	.	.	.	0.84
Zn	0.70	.	.	—0.38	.	—0.31	.	—0.47	.
Ni	.	.	0.60	0.86	0.85	0.68	0.88	0.28	0.73
Co	0.26	.	0.76	.	0.35	.	0.62	.	0.55
S	.	.	.	.	.	.	.	.	.
%	15	10	15	15	19	19	15	26	11

	6 68*1	6 70*1	6 72*2	7 02*4	7 04*1	7 16*3	7 28*4	7 36*4	7 38*2
SiO_2	.	—0.59	—0.83	.	.	.	.	.	.
TiO_2	—0.69	—0.50	—0.50	.	.	0.28	.	.	0.29
Al_2O_3	—0.84	—0.42	.	.	0.86	0.34	.	0.27	.
Cr_2O_3	0.94	.	.	.	—0.45	—0.25	.	.	.
FeO	.	0.42	0.37	—0.32	—0.50	.	.	0.58	.
MnO	0.36	0.26	.	—0.35	—0.57	—0.29	.	0.58	.
MgO	0.90	0.64	0.85	.	—0.62	.	.	.	—0.45
CaO	.	—0.33	.	.	.	.	.	.	—0.41
SrO	—0.74	.	.	0.82	0.94	0.87	0.86	0.71	0.85
BaO	—0.43	.	—0.34	.	.	0.27	.	0.25	0.63
Na_2O	—0.73	—0.43	—0.74	0.72	0.93	0.41	0.35	0.64	0.66
K_2O	.	.	—0.37	.	.	.	.	.	0.56
P_2O_5	—0.74	.	—0.42	0.38	0.39	0.84	0.63	.	.
ZrO_2	—0.51	.	—0.42	0.69	0.92	0.77	0.62	0.60	0.84
Cu	.	0.25	.	.	.	.	.	0.33	.
Zn	.	0.74	.	.	.	.	.	.	.
Ni	0.78	0.83	0.95	.	.	.	.	.	.
Co	0.65	0.85	0.95	.	.	.	.	.	.
S	.	.	0.30	.	.	.	.	.	.
%	39	37	19	10	30	10	7	7	17

	7 44*1	7 70*3	7 71*1	7 18*2	8 34*1	8 40*1	8 68*2	8 72*1	9 02*3
SiO_2	.	.	.	0.46	.	0.25	0.53	0.39	.
TiO_2	0.51	.	0.40	.	0.71	0.47	.	0.64	0.32
Al_2O_3	0.91	0.74	0.92	.	.	.	.	.	0.81
Cr_2O_3	—0.89	.	—0.69	—0.40	—0.37	.	.	—0.59	.
FeO	—0.26	—0.25	—0.27	—0.41	.	.	.	0.36	.
MnO	—0.57	—0.28	—0.60	.	.	.	.	.	.
MgO	—0.93	—0.28	—0.73	—0.43	—0.46	—0.33	—0.27	—0.44	.
CaO	.	.	.	0.54	—0.39	—0.53	—0.92	—0.82	—0.38
SrO	0.94	0.85	0.83	0.51	0.88	0.29	.	.	.
BaO	.	.	0.30	0.78	0.80	0.87	0.58	0.78	.
Na_2O	0.80	0.64	0.70	0.26	0.50	0.51	0.54	0.49	.
K_2O	.	.	.	.	0.61	0.85	0.81	0.79	0.88
P_2O_5	0.51	0.35	0.27	0.36	0.88	0.67	.	0.74	0.60
ZrO_2	0.82	0.64	0.61	0.27	0.88	0.70	0.63	0.83	0.44
Cu	.	.	.	—0.26	.	.	.	.	.
Zn	0.37	.	.	—0.78	0.75	0.77	0.83	0.74	.
Ni	—0.61	.	—0.43	—0.33	.	.	.	.	.
Co	—0.31	.	.	—0.33	.	.	0.35	.	.
S	.	.	.	.	.	.	.	.	.
%	39	12	40	7	41	32	16	40	14

	9	9	9	9	9	9	9	9	9
	16*4	32*4	46*3	50*4	64*3	12*3	24*4	34*3	36*1
SiO_2	0.38	0.39	0.75	0.52	.	.	.	0.92	0.64
TiO_2	.	.	.	.	.	.	.	−0.34	.
Al_2O_3	0.32	.	−0.56	.	.	.	.	.	.
Cr_2O_3	.	.	.	.	.	.	0.80	.	.
FeO	.	.	.	.	.	.	.	−0.75	−0.29
MnO	.	.	.	.	.	−0.45	.	−0.47	−0.53
MgO	.	.	.	.	.	.	.	−0.35	−0.35
CaO	.	−0.28	−0.83	−0.70	−0.56	−0.34	.	−0.64	−0.82
SrO	.	.	.	.	.	0.67	.	.	.
BaO	0.84	0.74	0.56	0.56	0.62	0.79	.	.	0.77
Na_2O	.	.	.	.	.	.	.	0.44	.
K_2O	0.90	0.90	0.83	0.77	0.74	.	.	0.37	0.87
P_2O_5	0.25	0.34	.	0.32	0.79	0.35	.	.	.
ZrO_2	0.35	0.42	0.41	.	.	0.77	.	.	0.63
Cu	.	.	.	.	.	.	.	.	.
Zn	.	.	.	.	.	0.56	−0.75	.	0.36
Ni	.	.	.	.	.	.	.	.	.
Co	.	−0.34	.	.	.	.	.	.	.
S	.	.	.	.	−0.38	0.32	.	.	.
%	8	10	15	9	12	13	7	10	28

	9	9	9	10	10	10	10	11	11
	44*2	58*4	74*4	48*1	56*2	74*2	42*4	06*2	50*3
SiO_2	0.32	0.74	0.26	.	−0.30	−0.54	−0.86	0.34	.
TiO_2	.	.	−0.30	−0.35	.	.	.	0.66	0.90
Al_2O_3	−0.30	.	−0.29	0.75	0.46	0.87	.	.	.
Cr_2O_3	.	0.58	.	.	−0.38	−0.47	0.29	.	.
FeO	0.39	−0.37	.	−0.90	−0.52	−0.28	.	.	.
MnO	0.56	.	−0.40	−0.72	−0.43	−0.49	.	.	.
MgO	.	−0.38	.	−0.30	.	.	0.47	−0.36	−0.26
CaO	−0.85	.	−0.27	0.85	0.80	0.69	0.89	.	.
SrO	.	.	.	0.84	0.85	0.88	0.52	.	0.52
BaO	0.62	.	.	−0.26	.	−0.34	.	0.73	0.46
Na_2O	0.43	.	.	.	.	.	−0.43	0.25	.
K_2O	0.72	0.80	0.56	−0.54	.	−0.53	−0.29	0.74	.
P_2O_5	0.44	.	0.72	.	.	.	.	0.87	0.89
ZrO_2	0.31	.	0.73	0.78	0.81	.	.	0.69	0.80
Cu	.	.	−0.28	.	−0.29	.	.	.	.
Zn	.	.	0.39	−0.40	.	.	−0.37	.	0.37
Ni	.	.	.	.	−0.27	.	.	.	.
Co	−0.33	.	−0.26	.	.	.	.	.	.
S	.	.	.	.	.	.	.	.	.
%	19	7	9	39	16	19	10	14	11

	11	11	11	11	11	11	11	12	12
	52*4	54*3	56*3	64*4	70*2	14*3	42*1	53*1	54*1
SiO_2	.	0.36	.	0.37	0.26	.	.	0.73	0.71
TiO_2	0.85	0.92	0.88	0.85	0.58	0.82	0.63	.	.
Al_2O_3	.	.	.	.	.	0.39	—0.25	0.97	0.90
Cr_2O_3	.	.	.	.	.	.	—0.53	—0.93	—0.89
FeO	.	.	.	.	—0.27	—0.26	0.28	—0.95	—0.93
MnO	.	.	.	.	—0.38	—0.77	.	—0.95	—0.92
MgO	.	—0.38	—0.33	—0.32	.	—0.35	—0.41	—0.95	—0.80
CaO	.	.	.	0.26	.	0.57	.	0.93	0.84
SrO	.	.	.	.	0.32	0.34	0.31	0.96	0.91
BaO	0.69	0.79	0.77	.	0.77	.	0.87	.	0.33
Na_2O	.	0.27	.	.	0.28	0.26	.	0.95	0.86
K_2O	.	0.71	0.71	0.37	0.84	.	0.71	.	0.34
P_2O_5	0.86	0.86	0.87	.	0.74	.	0.82	.	.
ZrO_2	0.59	0.50	.	.	0.56	.	0.75	0.88	0.70
Cu	.	—0.25	.	.	.	.	.	.	—0.39
Zn	—0.38	0.30	.	—0.50	.	.	0.58	.	.
Ni	.	—0.29	.	.	.	—0.27	.	—0.30	—0.43
Co	.	—0.31	.	—0.34	.	—0.38	0.53	.	—0.42
S	.	—0.26	.	.	.	.	.	.	—0.34
%	11	21	10	7	14	9	28	49	46

	12	12	12	12	12	13	13	13	13
	64*1	06*1	50*1 *****	52*1	56*1 *****	10*2	38*4	48*3	04*3
SiO_2	0.87	0.67	0.73	—0.28	0.86	0.28	.	.	.
TiO_2	.	0.42	.	.	.	0.48	.	.	0.29
Al_2O_3	0.94	0.86	0.92	0.95	0.75	0.61	0.89	0.44	.
Cr_2O_3	—0.92	—0.80	—0.79	—0.85	—0.79	—0.86	—0.66	—0.29	—0.68
FeO	—0.91	—0.51	—0.93	—0.34	—0.51	.	.	.	.
MnO	—0.84	.	0.76	—0.48	—0.48	.	.	.	.
MgO	—0.92	—0.88	—0.89	—0.94	—0.86	—0.48	—0.60	—0.74	—0.67
CaO	0.62	0.90	0.56	0.96	.	.	.	.	0.94
SrO	0.90	0.86	0.69	0.87	0.26	.	.	.	.
BaO	0.58	.	.	.	.	0.77	.	0.46	.
Na_2O	0.92	0.91	0.88	0.74	0.86	.	0.42	0.87	.
K_2O	0.33	0.41	.	.	0.40	0.77	.	0.48	.
P_2O_5	.	.	.	.	.	0.51	.	.	.
ZrO_2	0.88	0.48	0.38	0.53	0.33	0.33	.	.	.
Cu	—0.26	.	—0.37	.	—0.45	.	.	.	.
Zn	.	.	0.27	.	.	.	.	0.62	.
Ni	—0.42	—0.30	—0.49	.	—0.71	.	—0.33	—0.33	.
Co	—0.80	—0.57	—0.30	.	—0.55	.	—0.32	.	.
S	.	.	.	.	.	.	.	.	.
%	54	41	43	34	42	14	9	10	12

	13 20*4	13 68*4	13 74*1		09*1 XRF	09*2 XRF	09*3 XRF
SiO_2	.	0.29	0.70	SiO_2	0.63	.	0.62
TiO_2	0.32	.	.	TiO_2	0.51	.	—0.47
Al_2O_3	0.45	.	.	Al_2O_3	0.92	.	.
Cr_2O_3	.	.	.	Cr_2O_3	—0.86	—0.29	.
FeO	.	.	—0.71	FeO	—0.83	—0.42	—0.25
MnO	0.30	.	—0.39	MnO	—0.75	—0.38	—0.38
MgO	—0.43	.	—0.74	MgO	—0.79	-0.49	.
CaO	0.34	.	—0.27	CaO	0.75	.	—0.48
SrO	.	—0.41	.	SrO	0.88	.	—0.32
BaO	0.83	—0.37	0.32	BaO	.	.	0.53
Na_2O	0.25	.	0.88	Na_2O	0.56	0.38	—0.34
K_2O	0.67	.	0.52	K_2O	0.29	.	0.76
P_2O_5	.	.	.	P_2O_5	.	.	—0.50
ZrO_2	.	—0.26	0.59	ZrO_2	0.73	-0.41	.
Cu	.	0.84	.	Cu	—0.57	0.68	.
Zn	.	.	.	Ni	—0.57	0.79	.
Ni	.	.	.	Zn	—0.29	.	0.35
Co	.	.	—0.26	S	—0.29	0.90	.
S	.	.	.				
%	7	7	10		40	17	13

	55*1 XRF	55*2 XRF	55*3 XRF	60*1 XRF	60*2 XRF	60*3 XRF	62*1 XRF	62*2 XRF	62*3 XRF
SiO_2	0.26	—0.42	0.71	0.00	0.89	.	—0.31	-0.75	.
TiO_2	.	.	.	0.71	0.60	.	0.69	0.34	.
Al_2O_3	0.90	—0.26	.	0.67	0.65	.	0.91	.	.
Cr_2O_3	—0.84	.	—0.27	.	—0.68	.	—0.81	—0.44	.
FeO	—0.80	.	—0.30	—0.31	—0.80	.	.	0.92	.
MnO	—0.33	.	.	0.42	.	—0.55	.	0.88	.
MgO	—0.86	.	—0.35	—0.64	—0.73	.	—0.91	.	.
CaO	0.87	.	.	0.73	0.57	.	0.83	.	.
SrO	0.87	—0.28	.	0.95	.	.	0.88	.	.
BaO	0.44	—0.34	0.54	.	0.38	0.80	0.67	.	.
Na_2O	0.75	—0.35	.	0.73	0.57	.	0.93	.	.
K_2O	.	.	0.92	.	0.87	0.30	0.26	.	.
P_2O_5	0.54	.	.	0.48	.	0.67	0.48	.	.
ZrO_2	0.79	—0.32	0.30	0.87	.	.	0.89	.	.
Cu	.	0.92	.	.	.	.	—0.52	0.58	0.60
Ni	.	0.89	.	—0.70	—0.53	.	—0.74	.	0.44
Zn	.	.	.	—0.44	.	.	—0.35	0.68	.
S	—0.28	0.87	.	.	.	.	—0.39	0.70	0.47
%	47	12	9	51	15	9	43	12	10

Appendix 2. The mean compositions of the lithological groups by intrusion. The location codes are given in Table 1. Variables SiO_2—ZrO_2 are XRF data and Cu—S are AAS data. The variables SiO_2—S are XRF data if the group is provided with the code XRF.

	02*1	02*2	02*3	04*1	04*2	04*3	06*1
SiO_2	47.35	48.67	53.65	51.92	51.75	51.53	44.68
TiO_2	0.23	0.21	0.29	0.51	0.61	0.50	0.35
Al_2O_3	3.51	3.53	4.18	6.26	6.65	12.78	4.61
Cr_2O_3	0.78	0.66	0.45	0.33	0.17	0.09	0.55
FeO	12.68	11.47	9.48	11.73	11.22	9.39	13.88
MnO	0.21	0.18	0.18	0.22	0.22	0.17	0.19
MgO	29.49	29.49	21.53	19.86	16.18	13.40	31.56
CaO	3.42	4.22	8.89	7.66	11.62	9.64	3.08
SrO	0.0056	0.0061	0.0053	0.0109	0.0107	0.0316	0.0107
BaO	0.0466	0.0426	0.0389	0.0428	0.0439	0.0459	0.0359
Na_2O	0.2488	0.2428	0.3653	0.6956	0.7545	1.3523	0.5492
K_2O	0.9479	0.9183	0.7233	0.6030	0.5556	0.8750	0.1589
P_2O_5	0.0374	0.0405	0.0446	0.0526	0.0424	0.0572	0.0513
ZrO	0.0057	0.0059	0.0061	0.0069	0.0068	0.0114	0.0057
Cu	0.1049	0.0183	0.0231	0.0181	0.0415	0.0254	0.0147
Zn	0.0094	0.0078	0.0086	0.0048	0.0045	0.0055	0.0056
Ni	0.5741	0.0984	0.0848	0.0302	0.0419	0.0258	0.0696
Co	0.0219	0.0068	0.0058	0.0024	0.0035	0.0034	0.0054
S	3.13	0.40	0.71	0.25	0.53	0.56	0.16
n.	22	43	27	23	19	9	64

	06*2	06*3	06*4	06*5	10*1	12*1	12*2
SiO_2	43.66	49.90	50.54	49.93	46.88	41.73	45.49
TiO_2	0.55	0.46	0.79	0.72	0.32	0.42	0.32
Al_2O_3	5.27	7.43	9.13	11.19	4.79	3.45	3.31
Cr_2O_3	0.55	0.39	0.37	0.23	0.54	0.56	0.62
FeO	15.06	10.36	11.99	13.08	12.18	14.77	12.05
MnO	0.19	0.20	0.19	0.21	0.18	0.20	0.18
MgO	30.48	24.08	20.01	16.77	29.32	34.79	31.52
CaO	3.01	4.61	4.54	5.69	4.52	3.36	5.78
SrO	0.0111	0.0168	0.0200	0.0253	0.0083	0.0081	0.0076
BaO	0.0438	0.0444	0.0478	0.0434	0.0420	0.0403	0.0382
Na_2O	0.5515	0.8611	1.2235	1.4869	0.5446	0.3243	0.3446
K_2O	0.2817	0.3994	0.7917	0.4012	0.4139	0.1843	0.1740
P_2O_5	0.0919	0.0601	0.1605	0.0763	0.0334	0.0275	0.0255
ZrO_2	0.0077	0.0073	0.0108	0.0090	0.0051	0.0046	0.0049
Cu	0.0127	0.1236	0.0127	0.0151	0.0144	0.0126	0.0094
Zn	0.0086	0.0061	0.0049	0.0059	0.0068	0.0063	0.0081
Ni	0.0624	0.3754	0.0405	0.0343	0.0521	0.0473	0.0392
Co	0.0057	0.0115	0.0025	0.0021	0.0030	0.0066	0.0066
S	0.12	1.33	0.18	0.20	0.11	0.42	0.46
n.	40	16	21	26	41	9	8

	14*1	14*2	16*1	16*2	16*3	16*4	18*1
SiO_2	45.13	47.29	41.89	44.24	52.34	50.99	41.24
TiO_2	0.38	0.45	0.21	0.26	0.44	0.49	0.14
Al_2O_3	2.28	3.70	2.11	2.76	5.61	5.25	2.18
Cr_2O_3	0.29	0.28	0.44	0.24	0.33	0.39	0.91
FeO	14.64	13.88	15.43	15.02	10.73	9.69	15.01
MnO	0.26	0.20	0.19	0.21	0.19	0.18	0.21
MgO	29.09	23.91	37.36	32.49	22.49	21.26	39.03
CaO	7.26	9.13	1.86	3.90	6.25	10.73	0.87
SrO	0.0110	0.0174	0.0064	0.0079	0.0074	0.0090	0.0015
BaO	0.0425	0.0484	0.0414	0.0425	0.0478	0.0415	0.0099
Na_2O	0.3218	0.6056	0.1278	0.2532	0.4954	0.5583	0.1351
K_2O	0.1436	0.3175	0.1207	0.1368	0.8998	0.2551	0.1198
P_2O_5	0.0510	0.0899	0.0266	0.0321	0.0380	0.0363	0.0062
ZrO_2	0.0057	0.0086	0.0039	0.0041	0.0054	0.0049	0.0030
Cu	0.0099	0.0107	0.0057	0.0236	0.0139	0.0095	0.0124
Zn	0.0101	0.0072	0.0105	0.0101	0.0063	0.0052	0.0098
Ni	0.0194	0.0164	0.0637	0.0979	0.0412	0.0305	0.0280
Co	0.0074	0.0048	0.0097	0.0112	0.0051	0.0033	0.0134
S	0.50	0.38	0.17	1.07	0.71	0.37	0.67
n.	15	9	19	24	15	33	17

	18*2	18*3	20*1	20*2	20*3	24*1	24*2
SiO_2	43.19	47.74	41.60	46.09	45.81	44.25	45.02
TiO^2	0.20	0.24	0.19	0.17	0.26	0.13	0.14
Al_2O_3	1.99	2.73	2.18	1.93	2.84	1.46	1.62
Cr_2O_3	0.82	0.71	0.22	0.38	0.40	0.56	0.72
FeO	14.37	11.43	13.38	12.59	12.83	11.98	12.10
MnO	0.21	0.18	0.22	0.19	0.18	0.22	0.19
MgO	35.68	29.52	37.91	32.16	30.66	36.32	34.91
CaO	3.08	6.82	2.67	5.85	6.03	3.53	4.46
SrO	0.0042	0.0056	0.0058	0.0050	0.0076	0.0028	0.0030
BaO	0.0414	0.0382	0.0439	0.0396	0.0405	0.0416	0.0385
Na_2O	0.1527	0.2576	0.2563	0.2048	0.3882	0.1261	0.1271
K_2O	0.1028	0.1977	0.1585	0.1593	0.2602	0.1619	0.1241
P_2O_5	0.0120	0.0218	0.0092	0.0089	0.0206	0.0100	0.0111
ZrO_2	0.0034	0.0042	0.0035	0.0033	0.0047	0.0030	0.0027
Cu	0.0125	0.0117	0.3683	0.0405	0.0432	0.4302	0.1489
Zn	0.0070	0.0079	0.0138	0.0108	0.0110	0.0101	0.0049
Ni	0.0223	0.0152	0.4124	0.0598	0.0624	0.5565	0.2336
Co	0.0106	0.0073	0.0200	0.0076	0.0061	0.0235	0.0122
S	0.77	0.67	2.46	0.26	0.30	3.07	1.16
n.	19	15	6	30	20	33	36

	24*3	24*4	28*1	28*2	28*3	30*1	30*2
SiO_2	44.23	47.34	44.02	45.61	49.77	42.14	48.26
TiO_2	0.19	0.65	0.18	0.23	0.36	0.21	0.24
Al_2O_3	2.45	6.26	3.58	4.52	6.72	3.78	4.24
Cr_2O_3	0.41	0.37	0.60	0.62	0.48	0.39	0.57
FeO	14.25	11.34	10.98	11.16	8.73	12.42	10.10
MnO	0.21	0.19	0.18	0.18	0.16	0.18	0.18
MgO	33.76	24.81	33.46	30.51	21.30	35.81	25.95
CaO	3.78	7.69	6.12	6.03	10.79	4.08	9.15
SrO	0.0045	0.0117	0.0069	0.0087	0.0077	0.0098	0.0109
BaO	0.0403	0.0410	0.0399	0.0425	0.0414	0.0389	0.0450
Na_2O	0.2117	0.6446	0.2614	0.4151	0.6145	0.3852	0.4863
K_2O	0.2332	0.3828	0.0981	0.2097	0.3988	0.2194	0.5129
P_2O	0.0174	0.0562	0.0200	0.0347	0.0394	0.0528	0.0720
ZrO_2	0.0037	0.0073	0.0036	0.0053	0.0057	0.0042	0.0050
Cu	0.0363	0.0271	0.0269	0.0235	0.0167	0.0514	0.0311
Zn	0.0079	0.0051	0.0061	0.0056	0.0049	0.0067	0.0039
Ni	0.0617	0.0452	0.0547	0.0525	0.0285	0.0865	0.0680
Co	0.0067	0.0033	0.0057	0.0054	0.0026	0.0073	0.0086
S	0.35	0.58	0.24	0.25	0.31	0.29	0.21
n.	23	27	14	12	17	4	13

	30*3	32*1	32*2	32*3	34*1	34*2	34*3
SiO_2	52.05	45.82	50.26	47.75	49.44	53.88	50.65
TiO_2	0.27	0.28	0.36	0.60	1.55	1.35	1.71
Al_2O_3	5.74	3.37	4.48	7.43	12.75	15.16	15.58
Cr_2O_3	0.48	0.32	0.53	0.24	0.05	0.03	0.02
FeO	8.56	12.39	8.66	11.73	11.34	8.88	11.17
MnO	0.17	0.21	0.18	0.20	0.17	0.15	0.16
MgO	19.85	30.75	22.56	21.43	9.13	6.08	6.02
CaO	10.89	5.75	11.94	8.76	10.91	8.64	9.62
SrO	0.0112	0.0046	0.0062	0.0120	0.1003	0.1143	0.1107
BaO	0.0438	0.0404	0.0401	0.0422	0.0792	0.0967	0.0881
Na_2O	0.7741	0.2499	0.5008	0.8526	2.3948	3.4529	3.2095
K_2O	0.9310	0.3143	0.1843	0.4566	1.0183	1.3914	1.0241
P_2O_5	0.0883	0.0324	0.0299	0.0823	0.8267	0.6199	0.7627
ZrO_2	0.0058	0.0041	0.0046	0.0074	0.0333	0.0352	0.0310
Cu	0.0271	0.1540	0.1162	0.1081	0.0039	0.0042	0.0041
Zn	0.0035	0.0089	0.0036	0.0072	0.0033	0.0042	0.0044
Ni	0.0399	0.1828	0.1560	0.1121	0.0065	0.0031	0.0023
Co	0.0052	0.0144	0.0118	0.0086	0.0019	0.0014	0.0017
S	0.32	0.93	1.25	0.65	0.06	0.07	0.12
n.	14	35	31	14	7	21	19

	36*1	36*2	36*3	38*1	38*2	38*3	40*1
SiO_2	50.82	50.83	55.31	52.06	51.33	51.54	50.37
TiO_2	1.46	2.57	1.34	0.47	1.56	1.72	1.15
Al_2O_3	11.69	15.99	15.62	14.07	15.22	15.68	15.56
Cr_2O_3	0.14	0.02	0.03	0.09	0.04	0.02	0.04
FeO	10.79	12.37	10.12	8.41	11.71	10.94	9.90
MnO	0.19	0.18	0.16	0.17	0.20	0.19	0.15
MgO	11.90	5.26	5.22	10.58	6.67	5.63	7.91
CaO	11.03	9.17	8.13	12.48	10.28	9.32	11.04
SrO	0.0712	0.1019	0.0631	0.0504	0.0551	0.1013	0.1082
BaO	0.0685	0.1035	0.0786	0.0343	0.0602	0.0929	0.0574
Na_2O	2.7800	3.3944	3.4903	1.1794	2.3394	3.2856	2.4873
K_2O	1.4848	1.8387	1.6499	0.2850	0.4999	1.1973	0.6880
P_2O_5	0.5933	0.9301	0.4066	0.0739	0.1370	0.1566	0.4098
ZrO_2	0.0279	0.0395	0.0291	0.0123	0.0156	0.0341	0.0239
Cu	0.0088	0.0058	0.0054	0.2790	0.0052	0.0105	0.0070
Zn	0.0027	0.0038	0.0033	0.0049	0.0030	0.0045	0.0027
Ni	0.0097	0.0018	0.0020	0.0182	0.0032	0.0034	0.0043
Co	0.0016	0.0012	0.0011	0.0032	0.0014	0.0016	0.0015
S	0.06	0.06	0.06	0.21	0.13	0.09	0.08
n.	7	13	55	4	43	11	29

	40*2	42*1	42*2	44*1	44*2	46*1	46*2
SiO_2	51.91	51.76	53.56	47.00	46.54	52.25	53.05
TiO^2	1.57	1.49	1.56	1.16	2.22	0.89	1.48
Al_2O_3	14.54	15.50	16.94	11.69	17.64	15.64	16.71
Cr_2O_3	0.04	0.07	0.03	0.12	0.03	0.08	0.04
FeO	9.45	9.31	9.05	12.35	11.29	9.87	9.81
MnO	0.15	0.14	0.14	0.19	0.16	0.16	0.15
MgO	6.79	8.57	5.48	13.81	7.17	9.27	5.68
CaO	9.32	8.78	8.46	11.89	11.94	8.71	8.97
SrO	0.1275	0.1314	0.1144	0.0532	0.0986	0.0464	0.0455
BaO	0.1022	0.0801	0.0780	0.0450	0.0462	0.0516	0.0719
Na_2O	3.1238	2.2983	2.6308	1.2452	2.1739	2.0284	2.7542
K_2O	1.7432	0.8860	1.0024	0.1843	0.2049	0.6300	0.7895
P_2O_5	0.9201	0.6054	0.8471	0.1508	0.5275	0.3884	0.5239
ZrO_2	0.0386	0.0327	0.0360	0.0127	0.0200	0.0152	0.0200
Cu	0.0048	0.0026	0.0021	0.0880	0.0730	0.0018	0.0019
Zn	0.0057	0.0040	0.0040	0.0017	0.0025	0.0007	0.0011
Ni	0.0056	0.0057	0.0022	0.0166	0.0056	0.0019	0.0011
Co	0.0017	0.0021	0.0016	0.0031	0.0023	0.0006	0.0006
S	0.13	0.13	0.11	0.21	0.24	0.11	0.11
n.	21	8	27	27	35	113	222

	48*1	50*1	50*2	50*3	52*1	52*2	52*3
SiO_2	54.71	52.38	53.06	56.03	51.12	51.80	51.63
TiO_2	0.49	0.72	0.92	0.69	0.44	0.41	0.42
Al_2O_3	18.57	11.06	11.85	15.27	6.88	7.76	7.65
Cr_2O_3	0.08	0.39	0.29	0.10	0.50	0.54	0.47
FeO	5.78	9.47	9.46	6.66	12.96	11.03	12.01
MnO	0.11	0.18	0.17	0.13	0.23	0.21	0.20
MgO	8.34	16.57	14.34	9.30	23.24	23.23	21.92
CaO	8.00	6.34	6.72	8.19	3.56	3.53	3.71
SrO	0.1252	0.0413	0.0503	0.0646	0.0179	0.0234	0.0223
BaO	0.0674	0.0691	0.0714	0.0632	0.0435	0.0476	0.0432
Na_2O	2.8702	1.5006	1.7466	2.3579	0.7757	0.9420	0.5635
K_2O	0.7252	0.7949	0.8916	0.7901	0.2935	0.4155	1.3585
P_2O_5	0.1810	0.2410	0.3356	0.2527	0.0793	0.0789	0.0613
ZrO_2	0.0256	0.0140	0.0174	0.0188	0.0072	0.0880	0.0081
Cu	0.0187	0.0424	0.0092	0.0061	0.0078	0.0229	0.0051
Zn	0.0060	0.0048	0.0049	0.0061	0.0054	0.0050	0.0051
Ni	0.0250	0.0930	0.0255	0.0115	0.0169	0.0477	0.0087
Co	0.0037	0.0066	0.0020	0.0017	0.0026	0.0058	0.0016
S	0.74	1.41	0.31	0.63	0.31	0.84	0.13
n.	44	10	28	22	36	19	13

	52*4	52*5	54*1	54*2	54*3	54*4	54*5
SiO_2	51.68	53.35	45.76	48.54	51.44	52.71	53.50
TiO_2	0.43	0.52	0.80	0.72	1.26	0.81	1.01
Al_2O_3	8.76	17.81	9.18	10.29	12.21	15.99	16.88
Cr_2O_3	0.51	0.06	0.23	0.25	0.23	0.12	0.06
FeO	11.30	7.22	12.82	12.37	11.70	8.34	8.18
MnO	0.19	0.13	0.20	0.19	0.19	0.16	0.15
MgO	21.53	8.27	22.68	19.34	13.09	10.43	8.15
CaO	4.01	9.29	5.56	5.89	6.49	8.27	8.31
SrO	0.0289	0.0823	0.0293	0.0338	0.0433	0.0660	0.0708
BaO	0.0461	0.0454	0.0580	0.0555	0.0761	0.0634	0.0789
Na_2O	1.1455	2.6076	1.3311	1.3983	1.7277	2.0958	2.2982
K_2O	0.3690	0.4725	0.4254	0.4381	0.9407	0.6885	0.9601
P_2O_5	0.0770	0.1453	0.2674	0.2531	0.5832	0.3062	0.4365
ZrO_2	0.0099	0.0186	0.0126	0.0124	0.0175	0.0184	0.0214
Cu	0.0055	0.0055	0.1117	0.0261	0.0042	0.0056	0.0076
Zn	0.0043	0.0053	0.0078	0.0056	0.0059	0.0052	0.0079
Ni	0.0105	0.0041	0.3768	0.0896	0.0083	0.0162	0.0166
Co	0.0014	0.0012	0.0174	0.0047	0.0007	0.0014	0.0015
S	0.15	0.21	2.49	0.58	0.13	0.23	0.34
n.	43	38	20	15	22	29	9

	56*1	56*2	56*3	58*1	58*2	58*3	60*1
SiO_2	52.98	54.39	59.62	49.49	51.23	50.31	39.30
TiO_2	0.97	0.89	0.82	0.35	0.31	0.57	0.30
Al_2O_3	10.93	15.95	15.04	6.30	5.56	9.59	2.52
Cr_2O_3	0.14	0.03	0.02	0.43	0.42	0.26	0.38
FeO	9.89	7.31	7.87	10.08	8.28	10.35	18.49
MnO	0.18	0.14	0.15	0.19	0.18	0.18	0.23
MgO	14.33	8.22	6.21	26.39	25.83	20.41	36.50
CaO	7.86	9.82	6.19	5.37	6.32	5.99	1.63
SrO	0.0561	0.1007	0.0600	0.0132	0.0123	0.0373	0.0057
BaO	0.0703	0.0738	0.0681	0.0463	0.0465	0.0567	0.0398
Na_2O	1.5648	2.6408	3.3249	0.5871	0.5484	1.3979	0.1542
K_2O	0.8830	0.9381	1.1882	0.4323	0.3772	0.5874	0.2681
P_2O_5	0.2237	0.2090	0.1702	0.0461	0.0342	0.1107	0.0171
ZrO_2	0.0178	0.0258	0.0184	0.0058	0.0052	0.0117	0.0033
Cu	0.0086	0.0047	0.0061	0.0401	0.1995	0.0135	0.0115
Zn	0.0045	0.0041	0.0043	0.0028	0.0036	0.0016	0.0075
Ni	0.0174	0.0032	0.0023	0.1340	0.5164	0.0546	0.0261
Co	0.0012	0.0005	0.0006	0.0061	0.0164	0.0037	0.0067
S	0.16	0.13	0.17	0.56	2.71	0.21	0.22
n.	23	43	10	41	7	20	24

	60*2	64*1	64*2	64*3	64*4	66*1	66*2
SiO_2	39.83	41.86	46.47	51.13	52.86	42.81	42.91
TiO_2	0.40	0.36	0.53	0.52	0.37	0.05	0.07
Al_2O_3	3.23	2.84	5.87	6.68	13.01	0.71	0.79
Cr_2O_3	0.35	0.46	0.37	0.32	0.06	0.45	0.60
FeO	18.11	14.06	13.59	8.92	6.39	12.59	12.62
MnO	0.21	0.19	0.20	0.18	0.14	0.19	0.18
MgO	34.83	34.53	26.98	18.81	12.09	42.20	40.98
CaO	2.12	4.92	4.48	12.18	9.04	0.46	0.33
SrO	0.0066	0.0173	0.0271	0.0296	0.1233	0.0016	0.0009
BaO	0.0427	0.0494	0.0506	0.0411	0.0650	0.0408	0.0438
Na_2O	0.2244	0.3651	0.7424	0.8376	1.7771	0.0238	0.0150
K_2O	0.4389	0.2612	0.3958	0.1693	0.3782	0.0935	0.0453
P_2O_5	0.0356	0.0838	0.0769	0.0334	0.0793	0.0130	0.0072
ZrO_2	0.0037	0.0075	0.0083	0.0086	0.0228	0.0024	0.0023
Cu	0.0097	0.0104	0.0291	0.0093	0.0072	0.2198	0.2492
Zn	0.0071	0.0095	0.0078	0.0077	0.0076	0.0797	0.0118
Ni	0.0251	0.0379	0.0934	0.0322	0.0157	0.1711	0.8669
Co	0.0066	0.0067	0.0068	0.0040	0.0019	0.0136	0.0337
S	0.20	0.25	0.64	0.57	0.26	0.76	3.94
n.	12	30	12	11	26	41	27

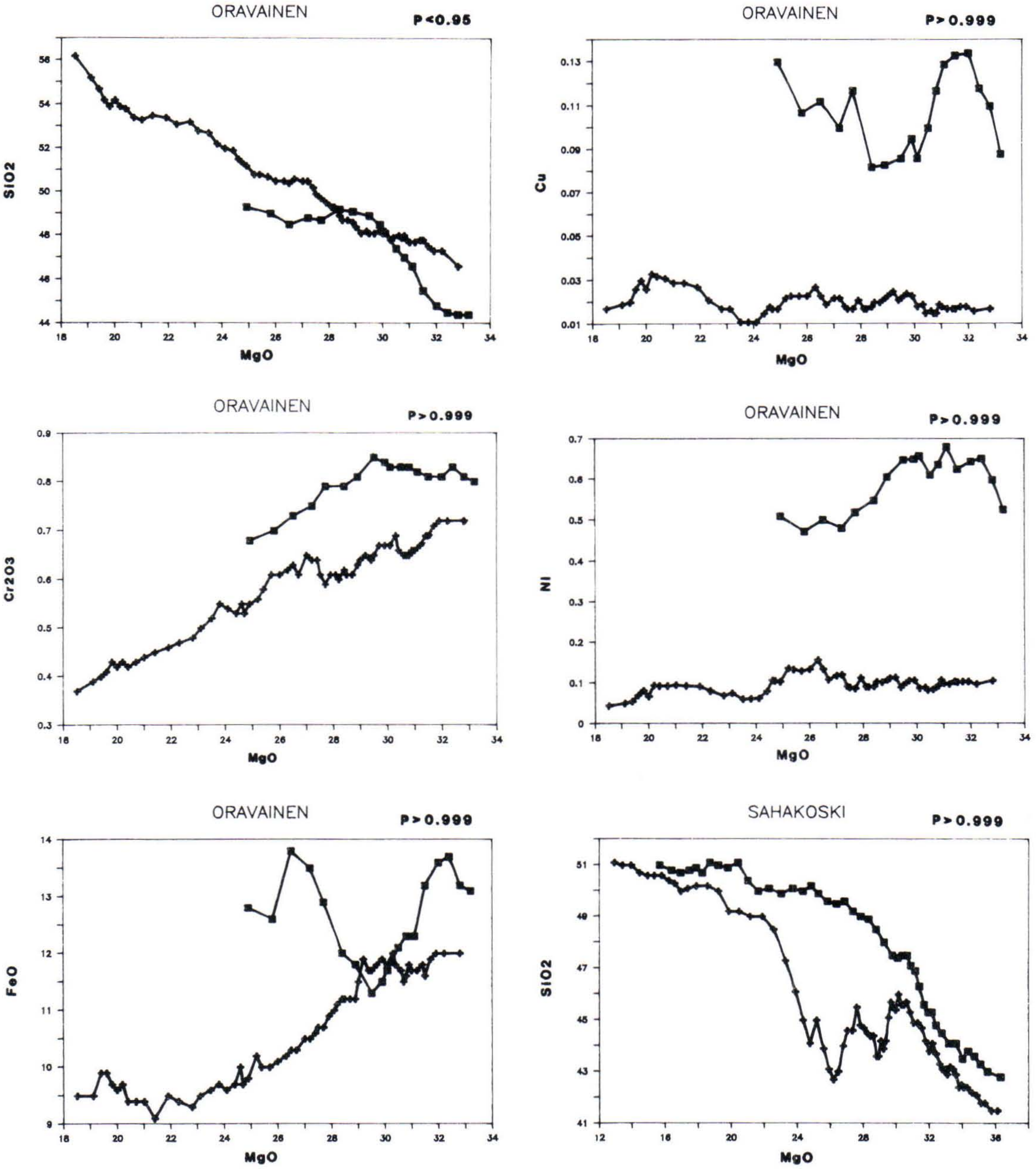
	66*3	68*1	68*2	68*3	70*1	70*2	70*3
SiO_2	45.26	51.52	49.81	53.30	46.58	49.11	50.65
TiO_2	0.17	1.19	1.68	1.32	0.46	0.67	0.70
Al_2O_3	2.13	14.24	14.27	15.56	5.45	6.26	8.59
Cr_2O_3	0.50	0.06	0.05	0.04	0.19	0.17	0.19
FeO	12.82	9.00	11.83	9.19	13.23	11.09	10.23
MnO	0.23	0.16	0.17	0.15	0.21	0.19	0.18
MgO	34.41	8.39	8.16	6.18	23.96	20.41	17.33
CaO	3.55	10.73	9.16	8.18	8.43	10.49	9.53
SrO	0.0053	0.0642	0.0715	0.0742	0.0203	0.0178	0.0375
BaO	0.0442	0.0757	0.0877	0.1233	0.0591	0.0469	0.0612
Na_2O	0.1286	2.5580	2.7487	3.1854	0.7477	0.8675	1.3558
K_2O	0.1047	0.9343	1.0576	1.6481	0.4591	0.6289	0.8637
P_2O_5	0.0180	0.3355	0.5364	0.4391	0.1040	0.0954	0.1730
ZrO_2	0.0033	0.0208	0.0235	0.0307	0.0090	0.0095	0.0151
Cu	0.1223	0.0051	0.0051	0.0048	0.0145	0.0064	0.0094
Zn	0.0126	0.0020	0.0035	0.0044	0.0066	0.0040	0.0040
Ni	0.3124	0.0040	0.0041	0.0035	0.0233	0.0067	0.0081
Co	0.0156	0.0011	0.0017	0.0015	0.0050	0.0010	0.0008
S	1.67	0.06	0.05	0.07	0.17	0.10	0.13
n.	17	17	13	26	13	41	54

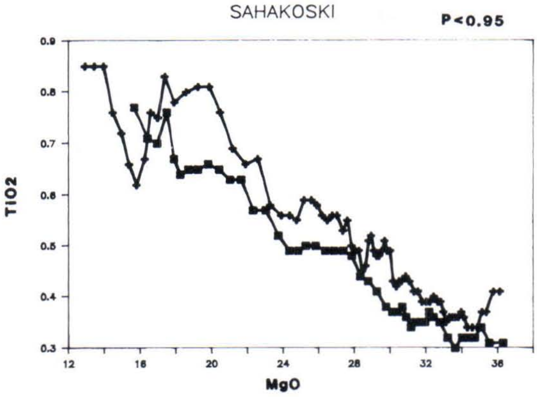
	70*4	72*1	72*2	72*3	72*4	74*1
SiO_2	50.21	46.77	49.64	52.93	55.39	51.72
TiO_2	0.95	0.48	0.48	0.65	1.14	0.87
Al_2O_3	14.65	17.05	19.51	17.23	17.16	18.20
Cr_2O_3	0.05	0.02	0.02	0.04	0.02	0.04
FeO	10.02	10.55	7.87	8.16	9.38	9.08
MnO	0.14	0.15	0.12	0.15	0.15	0.16
MgO	10.66	13.65	9.46	7.35	4.17	8.11
CaO	9.70	8.56	9.61	9.69	7.30	9.24
SrO	0.0720	0.0423	0.0571	0.0506	0.0538	0.0546
BaO	0.0955	0.0455	0.0506	0.0574	0.1557	0.0600
Na_2O	1.9710	1.7596	2.1577	2.4210	2.9558	2.4102
K_2O	0.9671	0.4917	0.7111	0.7657	2.3770	0.7374
P_2O_5	0.2482	0.0919	0.1003	0.1192	0.3935	0.1318
ZrO_2	0.0216	0.0112	0.0147	0.0141	0.0289	0.0137
Cu	0.0077	0.0036	0.0047	0.0040	0.0045	0.0034
Zn	0.0045	0.0033	0.0026	0.0024	0.0047	0.0027
Ni	0.0033	0.0299	0.0147	0.0051	0.0045	0.0063
Co	0.0007	0.0059	0.0035	0.0017	0.0018	0.0025
S	0.15	0.16	0.10	0.09	0.09	0.28
n.	45	9	12	23	18	27

	55*1 XRF	55*2 XRF	55*3 XRF	55*4 XRF	55*5 XRF	62*1 XRF
SiO_2	50.28	53.37	52.56	52.84	56.95	53.45
TiO_2	0.68	0.77	0.71	0.73	0.57	0.44
Al_2O_3	10.23	12.81	5.63	16.57	15.13	5.93
Cr_2O_3	0.28	0.21	0.13	0.10	0.13	0.51
FeO	11.73	10.64	8.08	8.45	7.65	9.66
MnO	0.14	0.13	0.13	0.11	0.09	0.17
MgO	15.71	13.33	9.77	8.91	8.72	25.01
CaO	5.75	6.44	7.55	8.43	6.29	3.60
SrO	0.0243	0.0363	0.0493	0.0567	0.0444	0.0224
BaO	0.0286	0.0407	0.0413	0.0505	0.0607	0.0658
Na_2O	1.2700	1.6887	1.9543	2.5086	2.2925	0.5151
K_2O	0.5779	0.6517	0.6709	0.6859	1.4149	0.7559
P_2O_5	0.1155	0.1033	0.1636	0.1609	0.1261	0.0945
ZrO_2	0.0051	0.0072	0.0089	0.0101	0.0095	0.0106
Cu	0.0971	0.0171	0.0776	0.0074	0.0105	0.0160
Ni	0.3803	0.0868	0.3146	0.0369	0.0541	0.1457
Zn	0.0151	0.0153	0.0204	0.0141	0.0177	0.0157
S	2.51	0.61	2.02	0.30	0.39	0.23
n.	62	66	37	77	18	37

	62*2 XRF	62*3 XRF	09*1 XRF
SiO_2	50.64	51.55	50.73
TiO_2	0.58	0.74	0.75
Al_2O_3	7.06	10.86	10.91
Cr_2O_3	0.29	0.17	0.24
FeO	12.90	10.13	12.86
MnO	0.23	0.18	0.19
MgO	21.71	16.04	15.04
CaO	4.71	7.44	4.94
SrO	0.0223	0.0745	0.0167
BaO	0.0860	0.1309	0.0311
Na_2O	1.0262	2.6677	1.2987
K_2O	0.7311	0.9432	0.8565
P_2O_5	0.0917	0.1253	0.0902
ZrO_2	0.0109	0.0281	0.0076
Cu	0.0344	0.0070	0.0888
Ni	0.1566	0.0384	0.1730
Zn	0.0179	0.0144	0.0228
S	0.9488	0.1397	1.6107
n.	26	17	54

Appendix 3. The element concentrations of the rocks rich in sulphides and poor in sulphides as a function of MgO. Square = rocks rich in sulphides, cross = rocks poor in sulphides. The name of the research target is marked at the upper margin of the figure. The SiO_2 and FeO contents of the groups formed from the total material are given at the end of the appendix. The element contents are in percentages.

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P<0.95
TiO2
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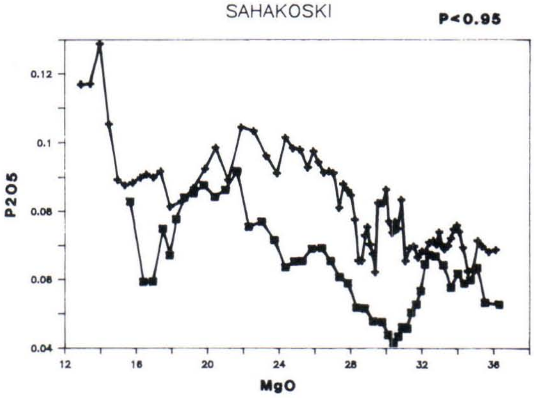
0.7
0.6
0.5
0.4
0.3
12
16
20
24
28
32
36
MgO


SAHAKOSKI
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P2O5
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0.1
0.08
0.06
0.04
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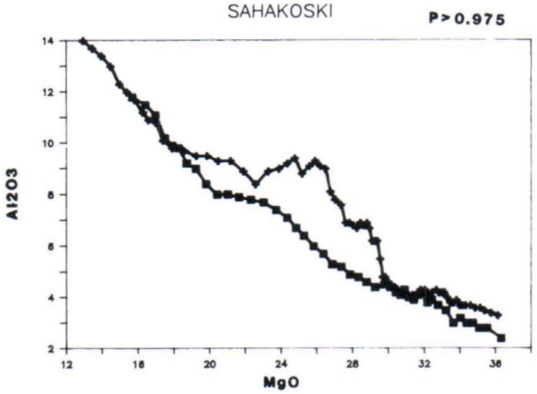
20
24
28
32
36
MgO


SAHAKOSKI
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Al2O3
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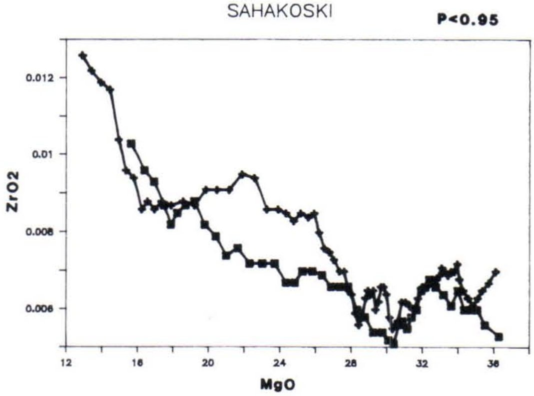
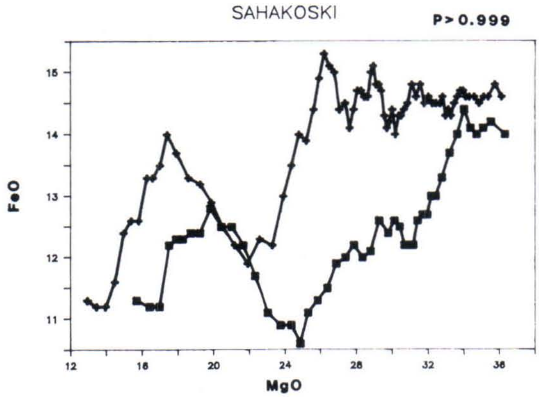
12
10
8
6
4
2
12
16
20
24
28
32
36
MgO


SAHAKOSKI
P<0.95
ZrO2
0.012
0.01
0.008
0.006
12
16
20
24
28
32
36
MgO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FeO
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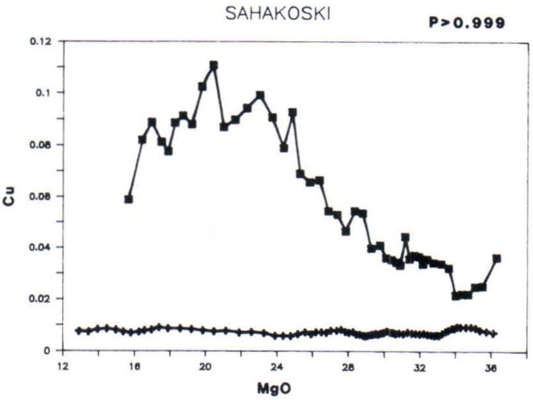
16
20
24
28
32
36
MgO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Cu
0.12
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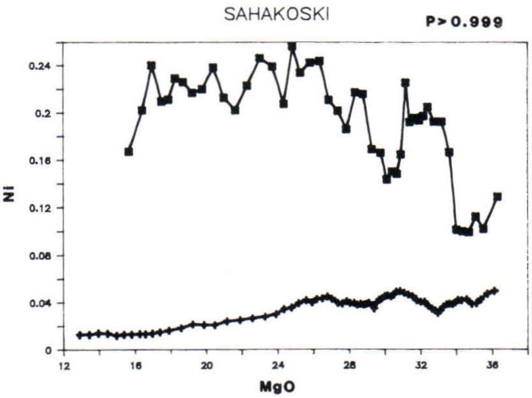
0.08
0.06
0.04
0.02
0
12
16
20
24
28
32
36
MgO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Ni
0.24
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0.16
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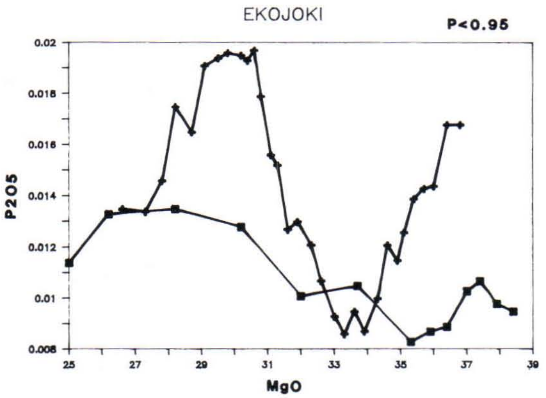
0.08
0.04
0
12
16
20
24
28
32
36
MgO


EKOJOKI
P<0.95
P2O5
0.02
0.018
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0.014
0.012
0.01
0.008
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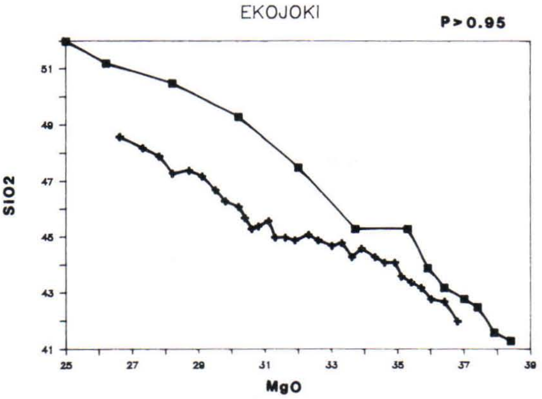
27
29
31
33
35
37
39
MgO


EKOJOKI
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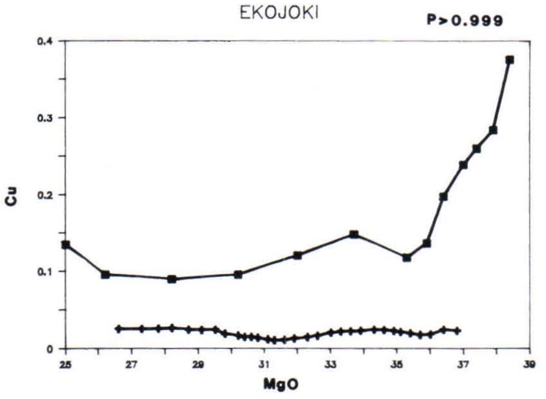
45
43
41
25
27
29
31
33
35
37
39
MgO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Cu
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0
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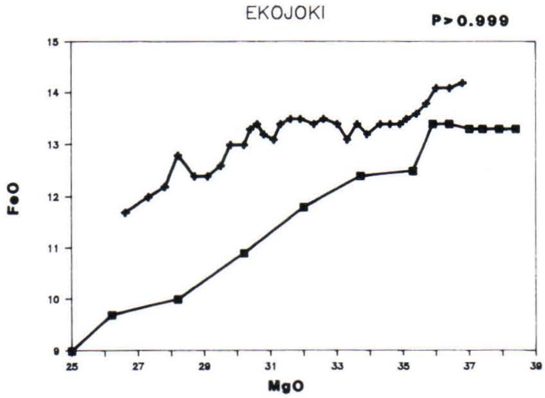
29
31
33
35
37
39
MgO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FeO
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11
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9
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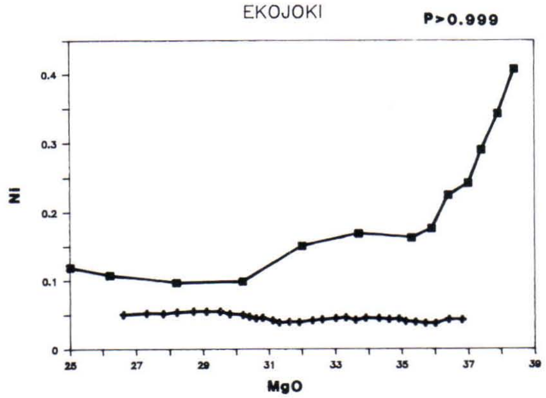
31
33
35
37
39
MgO


EKOJOKI
P>0.999
Ni
0.4
0.3
0.2
0.1
0
25
27
29
31
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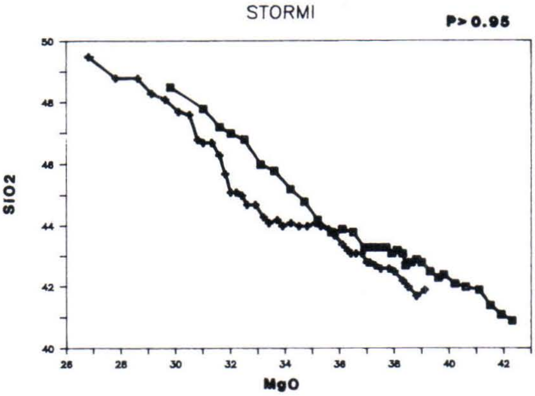
35
37
39
MgO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42
40
26
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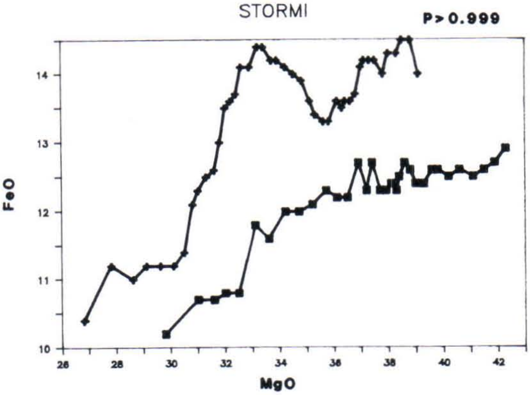
30
32
34
36
38
40
42
MgO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FeO
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40
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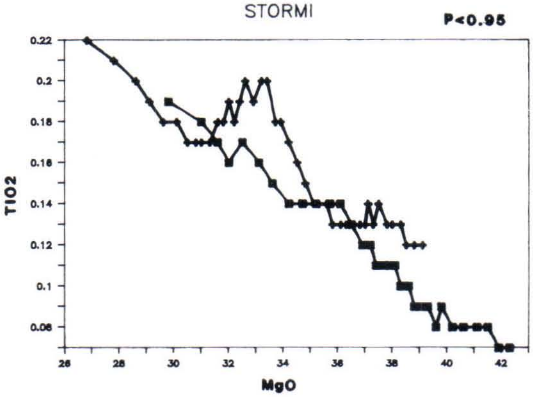
MgO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TiO2
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30
32
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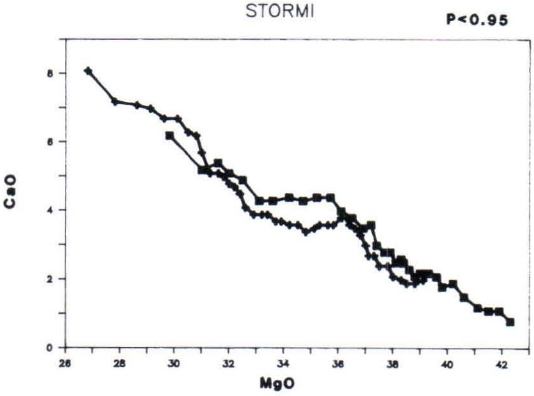
36
38
40
42
MgO


STORMI
P<0.95
CaO
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2
0
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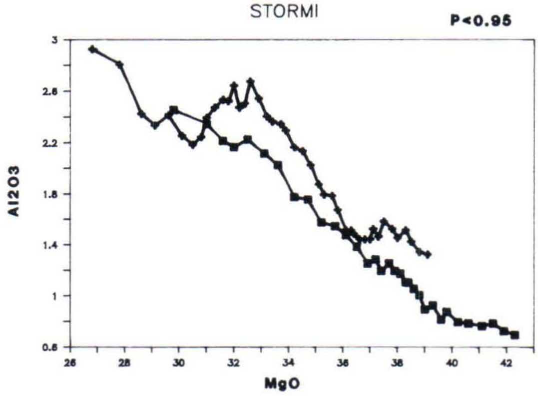
30
32
34
36
38
40
42
MgO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Al2O3
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1.8
1.4
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0.6
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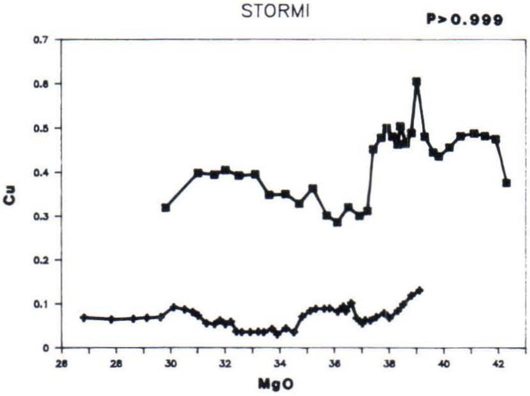
32
34
36
38
40
42
MgO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Cu
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0.4
0.3
0.2
0.1
0
26
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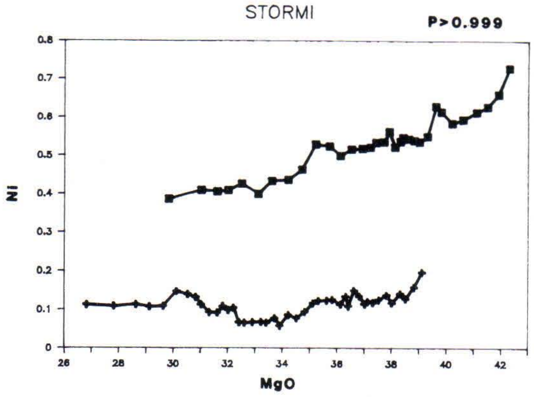
34
36
38
40
42
MgO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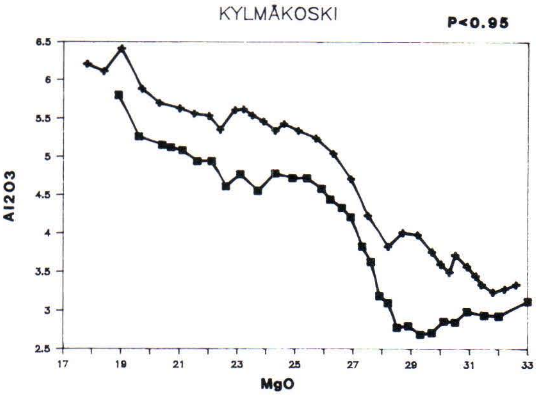
MgO


KYLMÅKOSKI
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Al2O3
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3.5
3
2.5
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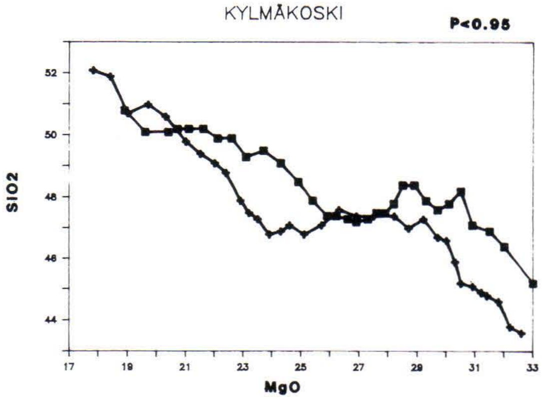
25
27
29
31
33
MgO


KYLMÅKOSKI
P<0.95
SIO2
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50
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44
17
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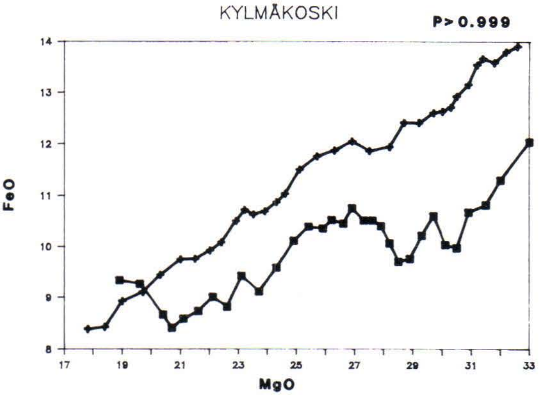
23
25
27
29
31
33
MgO


KYLMÅKOSKI
P>0.999
FeO
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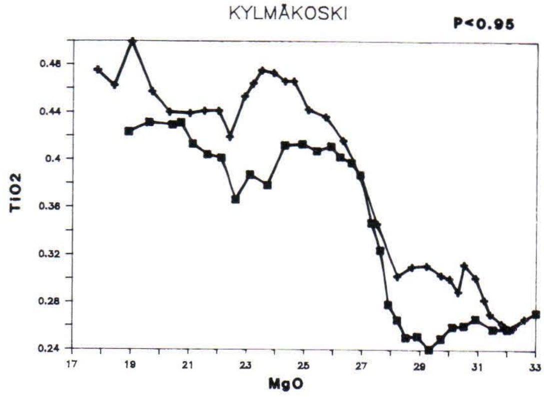
11
10
9
8
17
19
21
23
25
27
29
31
33
MgO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TIO2
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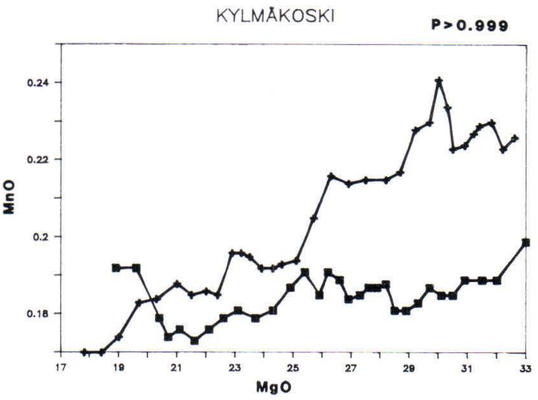
27
29
31
33
MgO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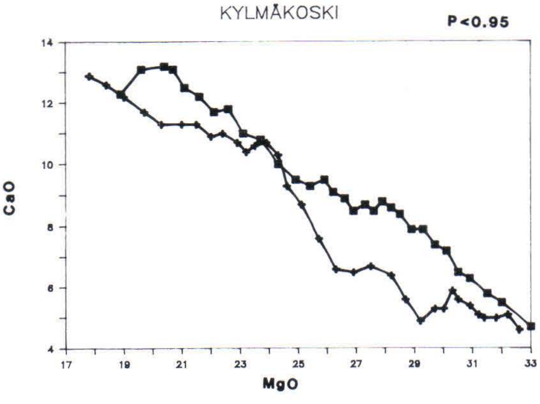
31
33
MgO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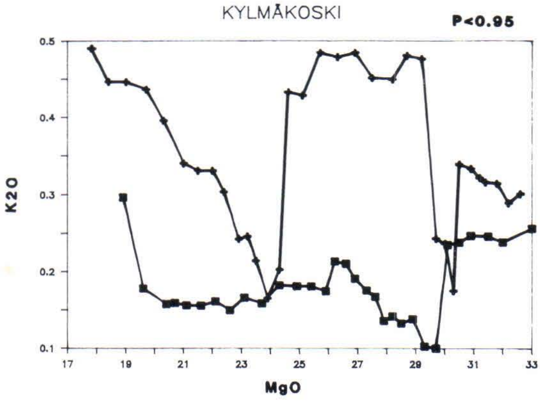
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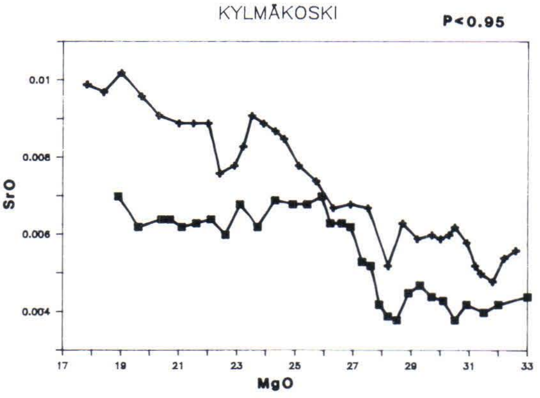
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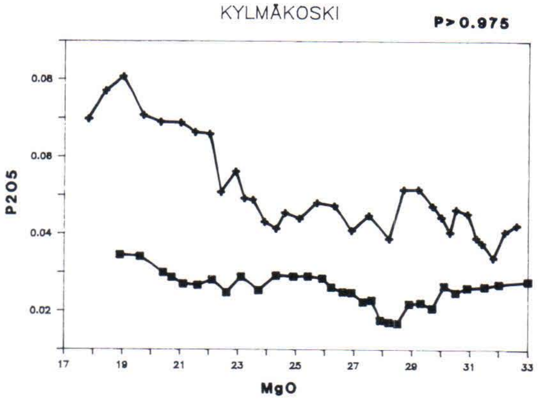
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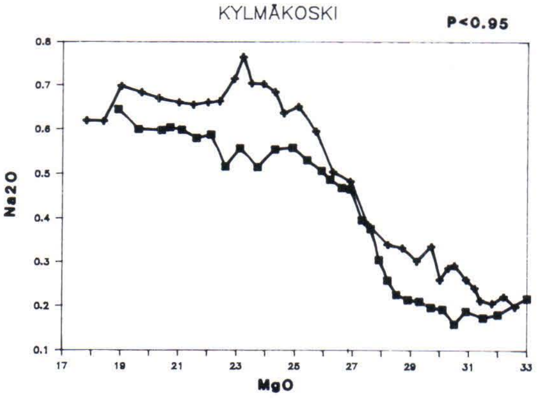
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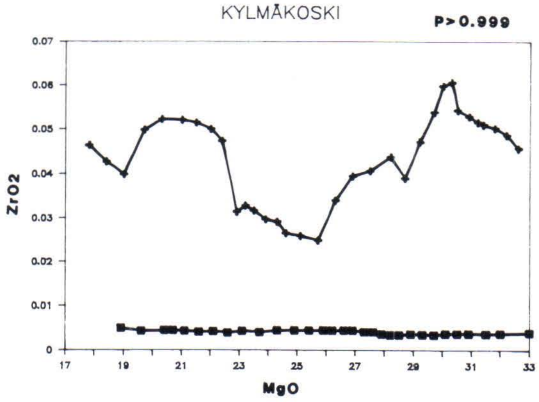
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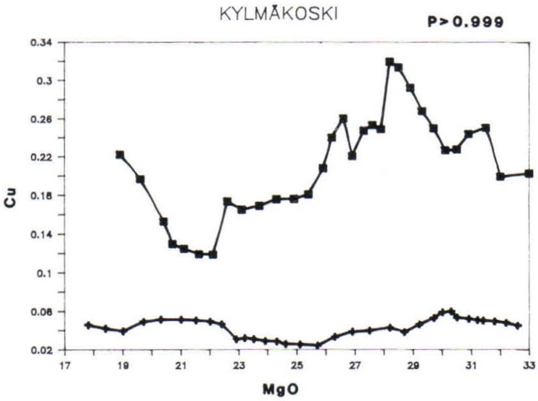
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0.02
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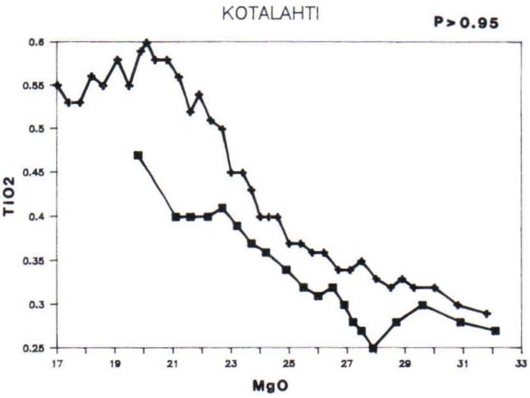
19
21
23
25
27
29
31
33
MgO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P>0.95
TIO2
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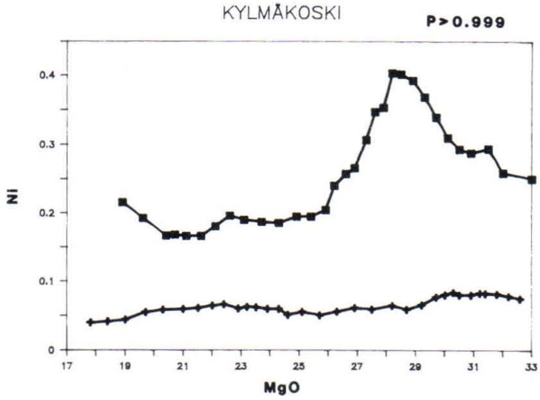
MgO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0.2
0.1
0
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21
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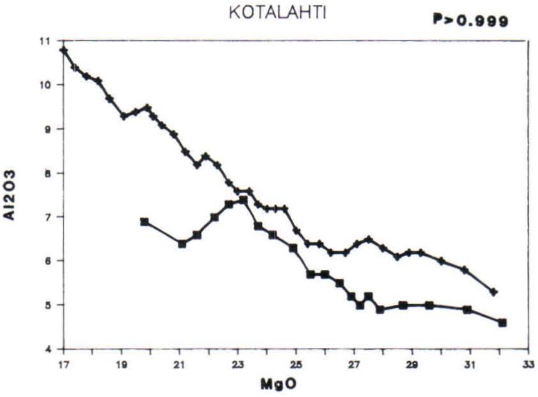
31
33
MgO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9
8
7
6
5
4
17
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21
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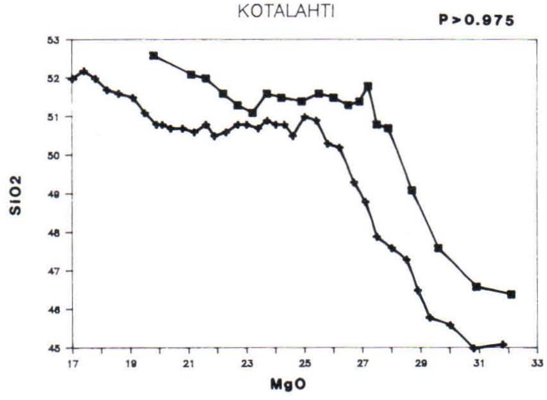
29
31
33
MgO


KOTALAHTI
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50
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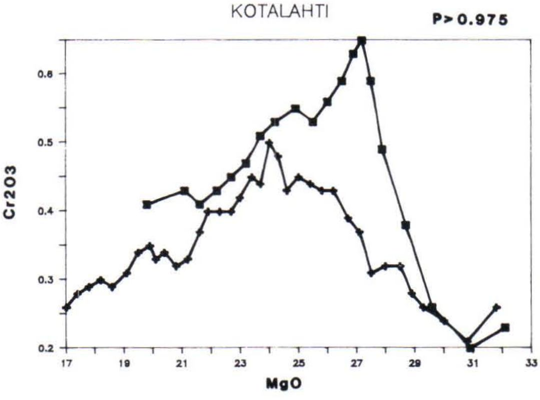
27
29
31
33
MgO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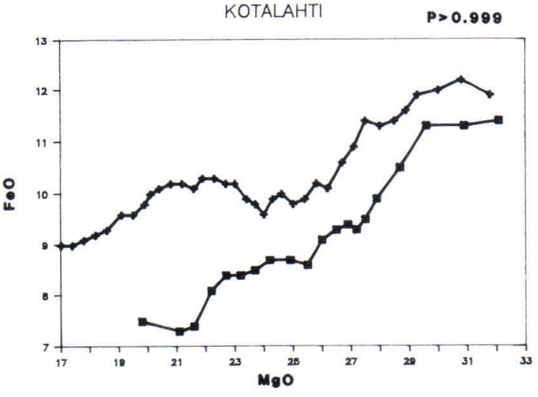
MgO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P>0.999
FeO
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12
11
10
9
8
7
17
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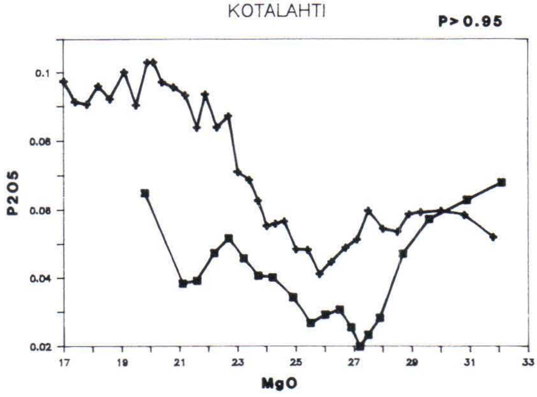
31
33
MgO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P>0.95
P2O5
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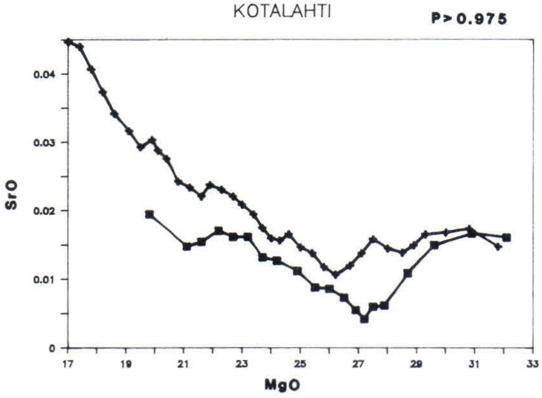
0.08
0.06
0.04
0.02
17
19
21
23
25
27
29
31
33
MgO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SrO
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0.03
0.02
0.01
0
17
19
21
23
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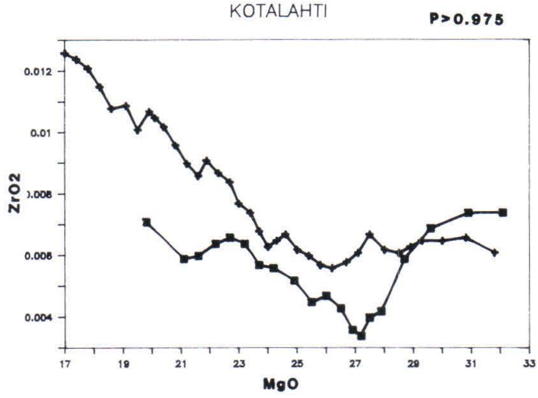
27
29
31
33
MgO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P>0.975
ZrO2
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0.01
0.008
0.006
0.004
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27
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31
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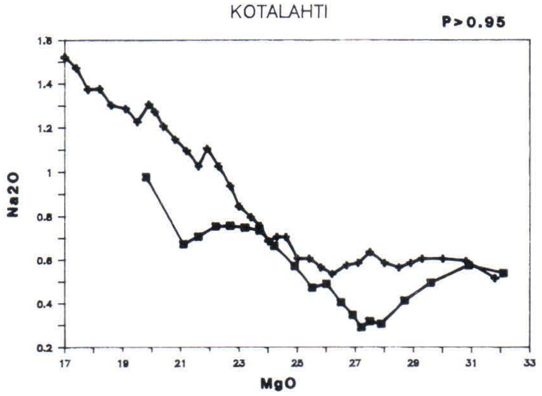
MgO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Na2O
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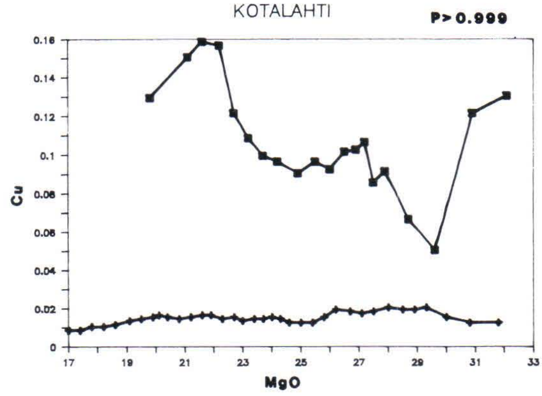
1.4
1.2
1
0.8
0.6
0.4
0.2
17
19
21
23
25
27
29
31
33
MgO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Cu
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0.1
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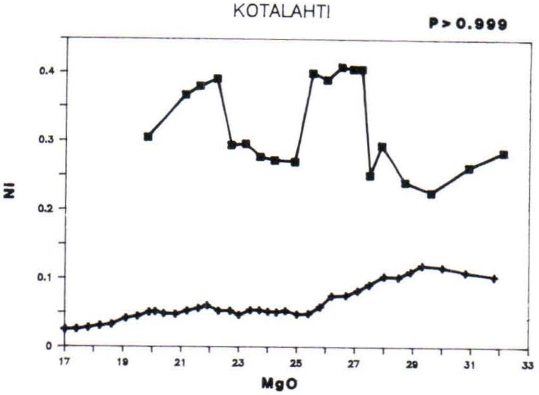
0.04
0.02
0
17
19
21
23
25
27
29
31
33
MgO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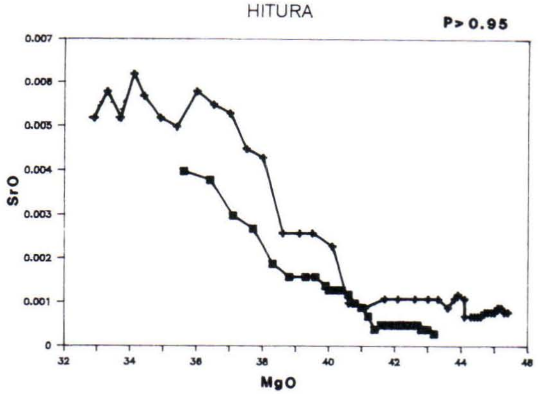
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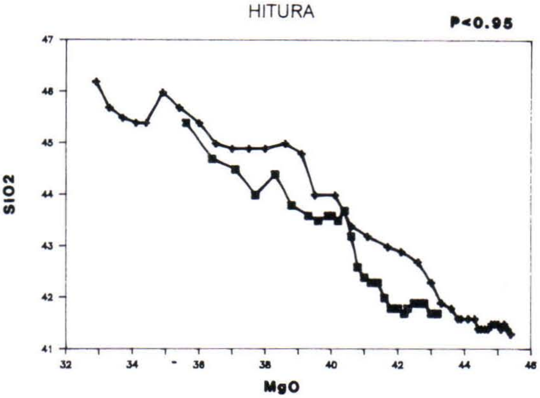
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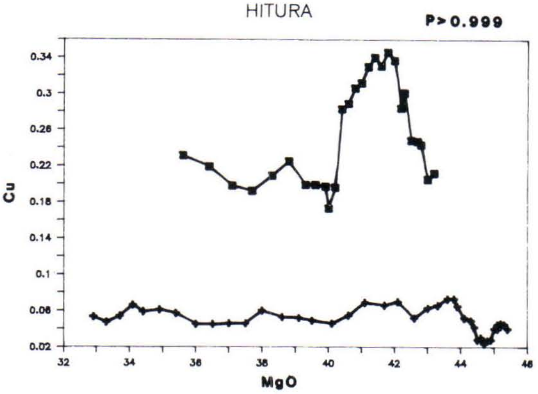
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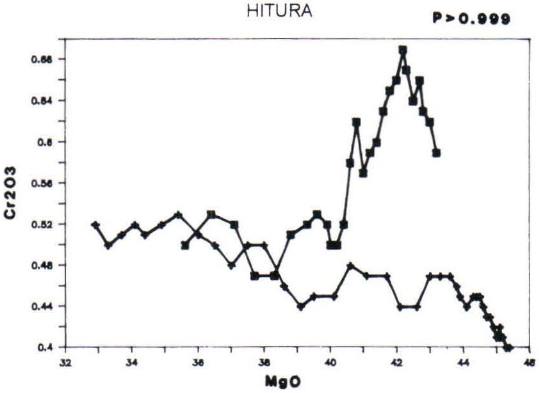
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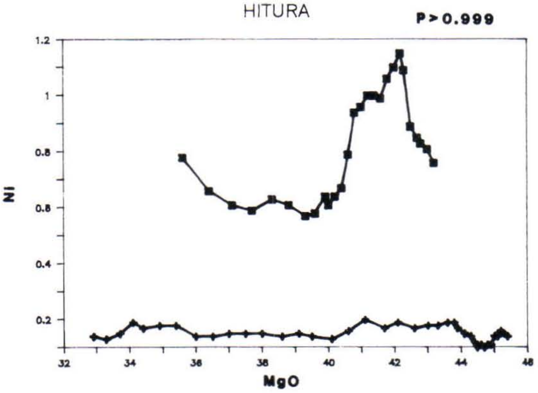
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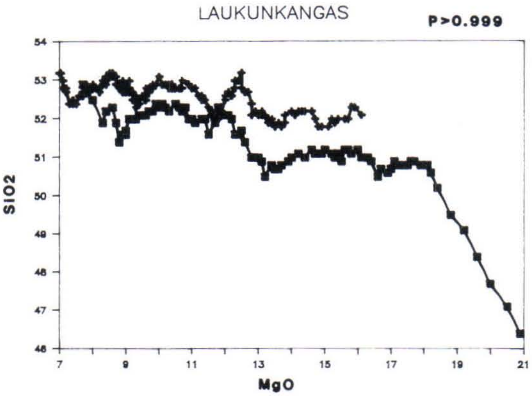
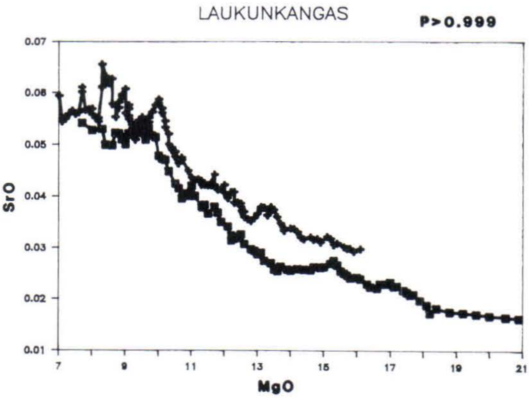

LAUKUNKANGAS
P>0.999
SIO2
54
53
52
51
50
49
48
47
46
7
9
11
13
15
17
19
21
MgO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SrO
0.07
0.06
0.05
0.04
0.03
0.02
0.01
7
9
11
13
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17
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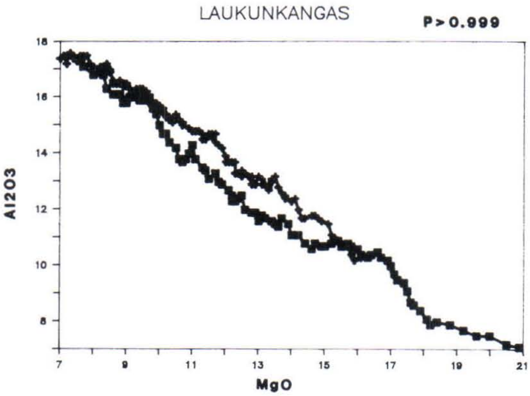
21
MgO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Al2O3
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16
14
12
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8
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9
11
13
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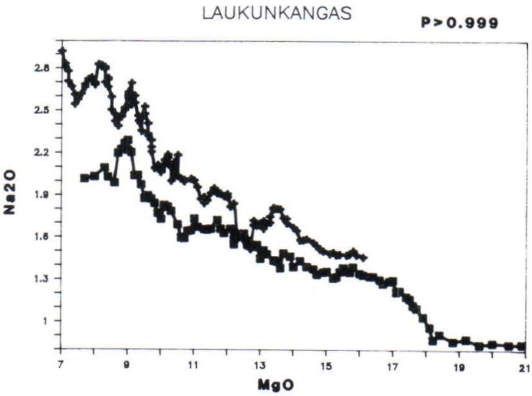
19
21
MgO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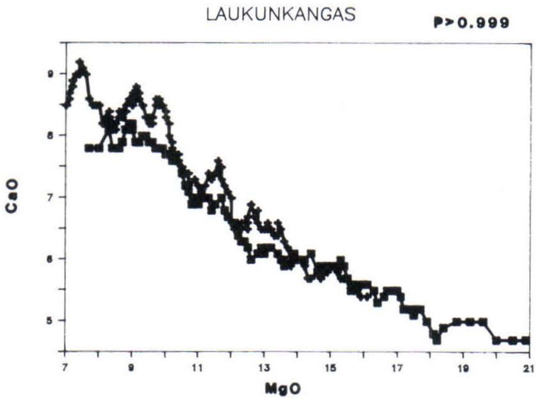
Na2O
2.8
2.5
2.2
1.9
1.6
1.3
1
7
9
11
13
15
17
19
21
MgO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CaO
9
8
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9
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17
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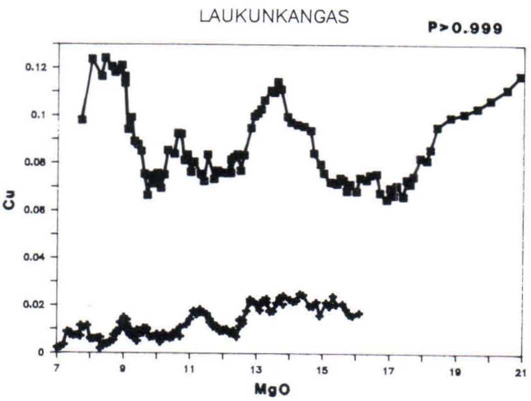
21
MgO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Cu
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0.08
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0
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9
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13
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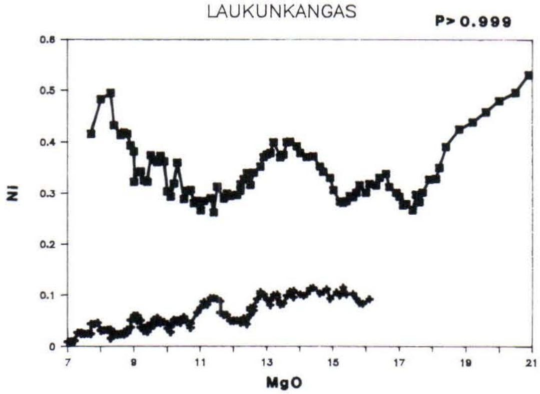
21
MgO


LAUKUNKANGAS
P> 0.999
Ni
0
0.1
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0.3
0.4
0.5
0.6
MgO
7
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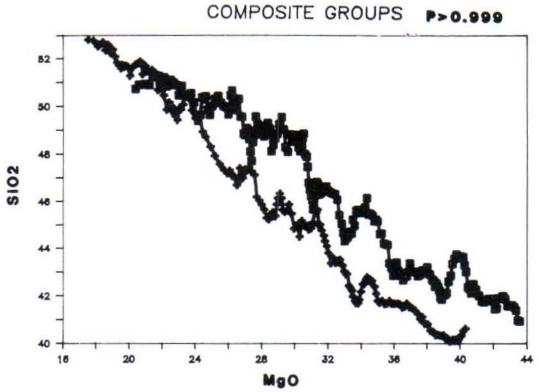
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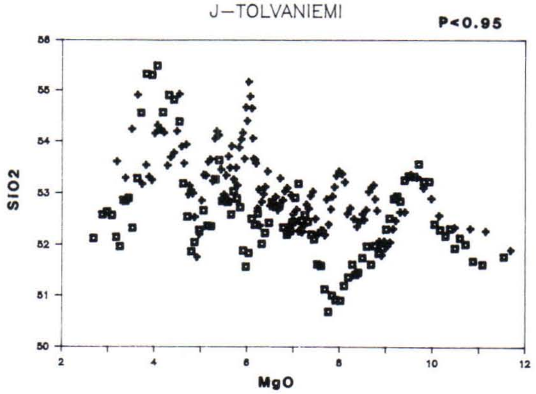
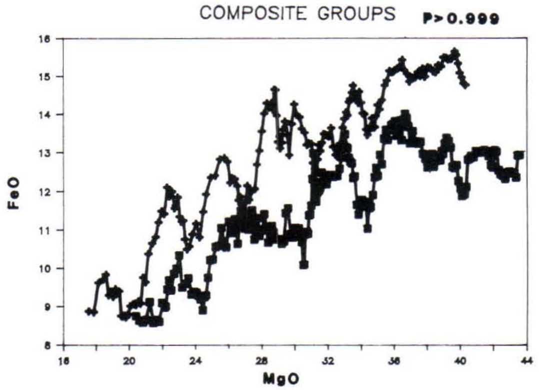
42
44
46
48
50
52
MgO
16
20
24
28
32
36
40
44


J-TOLVANIEMI
P<0.95
SiO2
50
51
52
53
54
55
56
MgO
2
4
6
8
10
12


COMPOSITE GROUPS
P>0.999
FeO
8
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11
12
13
14
15
16
MgO
16
20
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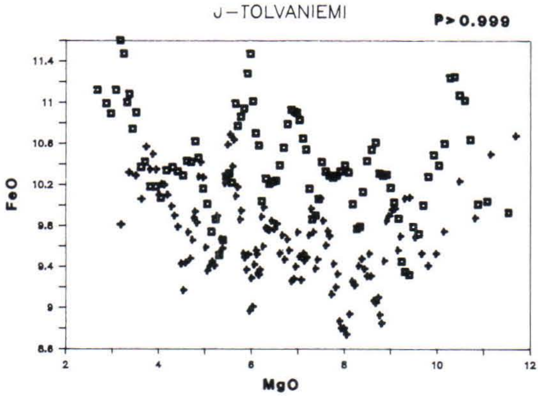
28
32
36
40
44


J-TOLVANIEMI
P> 0.999
FeO
8.6
9
9.4
9.8
10.2
10.6
11
11.4
MgO
2
4
6
8
10
12

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