Applying Lithogeochemical Discrimination Tools for Nickel-Copper Sulfide Exploration in Northern Finland

A Case study of First Quantum Minerals Exploration Targets

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Abstract

The Kevitsa-Satovaara complex is a mafic-ultramafic intrusion of age 2.05 Ga located in Central Lapland Greenstone Belt. The discovery of the Kevitsa ore mine resulted in opening the mine by First Quantum Minerals Ltd. (FQM) in 2012. Area has been under active exploration from 1990’s and number of smaller intrusions have been studied by geophysics, drilling and till sampling. Total number of 4220 samples of Kevitsa mine and 20 exploration targets and were selected from the database. The purpose of this research is to take a closer look on the new exploration targets by new geochemical tools.

Only a few elements were required for the geochemical tools used in this research: The rock forming elements Si, Al, Ca, K, Na, Ti, Fe, Mg and ore elements, Ni, Cu, Co, S. All the samples were analyzed by ICPMS methods and for less than 10% includes XRF analysis. Si is missing for more than 90% of samples which is modeled by a linear regression modeling and other elements.

Two new parameters were calculated from sulfide cumulates which are useful in monitoring sulfide segregation of magma. The Co#, 100*Co/(Co+Ni+Cu), shows the depletion of magma from Ni, and the Ni#, 100*Ni/(Ni+Cu), which shows the primitiveness of magma. In all targets except Ponostama, Co# number is very low (less than 7) which show an undepleted magma. For a few targets Ni# shows a komatiitic or combination of komatiitic and picritic composition with very high (90-100) Ni#. Also there is a trend toward the zero point of the Ni#-Co# graph which is very important in an economic Ni mineralization.

A new lithogeochemical test was developed by Lamberg (2005) for identification of fertile intrusion called fertility analysis. There are seven parameters in this analysis which quantifies all the evolution of magma toward an economic Ni mineralization. The Overall Discrimination value or OD value is then calculated by these parameters. OD value is range from 0.00 7.49 that shows how many steps the target passed. All FQM exploration targets and Kevitsa mine were tested by fertility analysis and ranked by OD value. 13 targets got very low OD value (1-1.99) that is due to very low sulfide content of magma. The magmatic studies of Kevitsa are also proved that very little amount of sulfide were dissolved in magma. Kevitsa mine got OD value 7 which proved the validity of the test and 4 targets got very high OD value (6.8-7). These targets belong to Satovaara and Puijärvi intrusions.

Keywords: Ni-Cu orthomagmatic deposits, ultramafic intrusion, Kevitsa mine, Fertility Analysis, Fennoscandian shield, Finland
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1. Introduction

Orthoagmatic deposits are the most important exploration targets for Ni, Cu and PGE in Finland. The Svecofennian Palaeoproterozoic orogenic deposits (1.9 Ga) have been mined for nickel and copper since early sixties with a total production of 43 Mt of ore at average grades of 0.7 % Ni and 0.3 % Cu. The total pre-mining resource of all the Svecofennian Ni-Cu deposits known to date is about 60 Mt at 0.7 % Ni. Recently closed Hitura has produced 15 Mt at 0.60 % Ni and 0.22 % Cu with remaining ore resources of 5 Mt at 0.7 % Ni and 0.2 % Cu. The largest closed mine is Kotalahti with a production of 12.4 Mt at 0.66 % Ni and 0.26 % Cu. The Kotalahti and Vammala Nickel Belts in central and southern Finland host several dozens of potential deposits, in some of which the average grade can be up to 2 % Ni. The deposits are hosted by mafic-ultramafic intrusions within migmatitic mica gneiss or in the contact zone of Archaean and Proterozoic rocks. (Lamberg, 2005)

The Archaean komatiites (ca 2.8 Ga) in eastern and northern Finland and the Palaeoproterozoic komatiites (ca 2.05 Ga) have been explored for nickel since the 1960. The largest deposit discovered is Ruossakero in northwestern Lapland with resources of 4.2 Mt at 0.52 % Ni. Numerous smaller deposits in komatiites and komatiitic basalts have been discovered in the Archaean greenstone belts of Kuhmo and Suomussalmi in eastern Finland. Low-grade disseminated occurrences have been found in the 2.05 Ga Pulju greenstone belt and growing interest is also shown for other belts of the same age (e.g. Sattasvaara). Also the komatiite-coeval, intrusion-hosted Keivitsa deposit contains a significant metal reserve (up to 432 Mt at 0.29 % Ni, 0.45 % Cu and 0.4 ppm PGM+Au). The possibility to find Pechenga-type deposits in northern Finland should also be kept in mind (Lehtinen, 2005).

First Quantum Minerals Ltd. is one of the leading copper producers in the world with worldwide activities in North America, Central Africa, Australia, Spain and Northern Finland with a global portfolio of copper, nickel and Platinum element assets. The activity of FQM in Finland started with Kevitsa project in 2008 and after beginning of commercial production of the mine in 2012, a large exploration project has been started on the intrusions around Kevitsa. The future global strategic plan is to produce more than 1.3 million tons per year of copper within five years; the company is poised to become the largest, widely-held pure-play copper producer and one of the top five copper producers in the world.

The purpose of this study is to evaluate and rank the exploration targets using the available lithogeochemical data and the analysis methods called the Fertility Analysis developed by Lamberg (2005). In addition, the method will give additional information on the characteristics of the parental magma and potential Ni mineralization. The hypothesis of the study is that it is possible to rank the exploration targets by using lithogeochemical data and identify the most potential ones for further exploration.
2. Geology of Northern Finland

The bedrock of northern Finland is part of Fennoscandian shield (Figure 1) and is composed mainly of Archean granite gneiss-greenstone terrain (known as Central Lapland greenstone belt or CLGB) and Paleoproterozoic schist belt which were mostly deposited on the Archean basement. CLGB contains several volcanic and sedimentary domains which only the domains related to volcanism of the exploration area are described below. (Lehtinen, 2005)

![Figure 1 The Fennoscandian Shield (Lehtinen, 2005)](image)

2.1. Archean-Proterozoic Volcanism

Late Archaean magmatism of Fennoscandian shield started by 2440-2490 Ma intrusion events by bimodal mafic-felsic volcanism and formed a boundary between Archaean and Proterozoic formations (Lehtinen, 2005). The Central Lapland greenstone belt (Figure 2) records depositional evolution for almost 600 Ma. Komatiitic lavas, basalts and high Mg basalt represent the mafic, and the rhyolites represent the felsic members. Mafic magmas formed layered sill-like intrusions with the clastic sediments most notably at 2220 Ma and 2050 Ma. Acid igneous rocks such as lavas, dykes and intrusions are spread in the shield but they are not correlated with layered intrusion. This volcanism was later overlayed by Kittila group volcanism.
2.2. Mafic Layered intrusion of Fennoscandian shield

The first group of mafic layered intrusion occurred in the ages of 2440-2490 Ma with the eruption of the rifting related Komatiitic to rhyolitic lavas on the Archaean craton basement. Koitelainen intrusion placed at the northeast of Kevitsa intrusion is an example of this event (Mutanen, 1997). Mafic intrusions were mainly emplaced along the unconformity contact between the basement and late Archaean metasediments. The parent magma of the intrusions was low in Ti and P, and the Fe$^{3+}$/Fe$^{2+}$ ratio was low. The magmas were also unsaturated in sulfur and terminal saturation of the sulfide liquid occurred at or above the magnetite-in phase contact. In this aspect the magmas were similar to the other large layered intrusions of tholeiitic affinity such as Bushveld. Later mafic dykes cut through the intrusions. Their contacts and petrography show beginning of a new magmatic activity.

The proceeding magmatic event that formed Kevitsa intrusion occurred in 2050-2200 Ma by bimodal rhyolitic-komatiitic volcanism. They exist in many places in northern Finland, particularly within the Savukoski group (Figure 3). There are numbers of variously shaped and sized intrusions, typically conformable dike like of a few of meters in thickness which are potentially of this age. The Kevitsa-Satovaara complex is currently the only representative of a sizeable mafic-ultramafic intrusion of 2.05-2.20 Ga age (Lehtinen, 2005).

The mafic layered intrusion of northern Finland and Russian Karelia host a variety of ore deposits. Of these Kemi has been mined for chromite since 1966. Mustavaara was mined for V and Ti for a short period in 1970-1985. Numerous subeconomic PGE, Ti, V, chromite and Ni-Cu sulfide deposits have been discovered in these provinces (Mutanen, 1997).
2.3. Sedimentary Formations
The main sedimentary structures of the area are part of two groups, Sodankylä and Savukoski group. Sodankylä metasediments deposited mostly on Salla or Onkamo groups. These sediments are represented by quartzite and mica-schist.

Savukoski metasediments include phyllites, black schist and mafic tuffits. Savukoski group is the first graphite- and sulfide-bearing group in the Paleoproterozoic stratigraphy of CLGB and has been suggested to provide an important sulfur source horizon for magmatic Ni-Cu-PGE deposits (Lehtinen, 2005).

![Figure 3 stratigraphy of CLGB. Magmatic and tectonic events are listed in the ages of 2.5-1.88 Ga (Lehtinen, 2005).](image)

2.4. Kevitsa Intrusion
The mafic intrusion of Kevitsa-Satovaara, located 34 km north of Sodankylä is the largest intrusion in the exploration area which has been studied in details by various researchers (Mutanen, 1997; Lamberg, 2005; Koivisto, 2012; Yang, 2013). Kevitsa is funnel shaped and has a surface area of 17 km² and maximum thickness of more than 2.5 km. Several exploration programs had been done on the deposits since 1960’s. Kevitsa mine began its operation in 2012 and exploration activity is still going on around the mine.

The Kevitsa and Satovaara intrusions represent blocks of a single intrusion separated by a zone of north-east fault. Comparing to Kevitsa, Satovaara is concentrated higher in stratigraphy and contains higher MgO in ultramafic cumulates. The 2D and 3D seismic study of the intrusion provided more evidence that two intrusions are related together. But there is no geochemical and age studies on Satovaara. (Malehmir, 2012)

The intrusion is divided into the marginal chill zone, ultramafic zone and gabbroic zone (Mutanen, 1997). The marginal chill zone at the lower contact of the intrusion consists of microgabbros, quartzgabbros and quartz rich pyroxenites. The lower part of the layered succession is occupied by ultramafic rocks, mainly olivine websterites and olivine clinopyroxenites. The overlaying gabbro zone comprises pyroxene gabbros and ferrogabbros. Graphites are only visible in the southwest of gabbroic zone (Figure 4).
The feeder dyke of the intrusion has not yet located. The chamber was filled as a single cast and no repetitive entries of magma have been found on the intrusion (Mutanen, 1997). The Kevitsa magma is formed by komatiitic magma extremely enriched with Ni which intruded into the sedimentary pile at about the level where the amounts of sulfides and graphites increases (Yang, 2013). The magma is affected by heavy contamination from crustal rocks such as volatiles (C, Cl, H2O) and certain trace elements (PGE-Au, S, Se, Te, Se, Ni, Co, V, REE, U). But with the lack of isotope studies it is not possible to determine the role of important elements (such as S) in the intrusion. Only the mineralogy studies show that graphite of the intrusion was originated from the magma.

In its upper part, the ultramafic zone contains a Cu-Ni-PGE sulfide deposit now known as the Kevitsa deposit. The ore is formed by disseminated sulfides with the sulfur grade rarely exceeding 3 wt%.

Mutanen (1997) designated three end members based on Ni content of sulfide fraction (shown as Ni_SF). The main ore body is called “Regular Ore” having Ni_SF between 4% and 7% and it forms the main mass of the deposit. The “Ni-PGE” part is very low in Cu but the Ni_SF is higher than 25 and it is enriched in PGE. The “false ore” has a low Ni_SF of 1-4%. The ore types represent a mixture of komatiitic dunite and pelitic sulfides. The element ratios suggest crustal contamination of the magma and substantial amount of sulfur was added into the magma. But sulfide liquid in the Kevitsa magma has a controversial role as a collector of PGE. In all ore types, PGE doesn’t correlate with sulfur content (Gervilla, 2005).

First Quantum Minerals completed the exploration projects on Regular ore and it became one of the largest base metal mineral discoveries in Finland’s history. The mineral reserve is 81 Mt proven ore with
grades of Ni 0.29%, Cu 0.4%. The details of mineral reserve are given in Table 1 Reserve characteristics of Kevitsa ore

Table 1 Reserve characteristics of Kevitsa ore (Cortesy of First Quantum Minerals, Report Dec 31, 2012)

<table>
<thead>
<tr>
<th>Ni Cut-off Grade of 0.13%</th>
<th>Tonnes (Mt)</th>
<th>% Ni</th>
<th>% Ni(S)</th>
<th>% Cu</th>
<th>% Au</th>
<th>% Pd</th>
<th>% Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proven</td>
<td>81.0</td>
<td>0.29</td>
<td>0.26</td>
<td>0.40</td>
<td>0.13</td>
<td>0.17</td>
<td>0.23</td>
</tr>
<tr>
<td>Probable</td>
<td>76.0</td>
<td>0.33</td>
<td>0.30</td>
<td>0.42</td>
<td>0.12</td>
<td>0.18</td>
<td>0.25</td>
</tr>
<tr>
<td>Total Proven &amp; Probable</td>
<td>157.0</td>
<td>0.31</td>
<td>0.28</td>
<td>0.41</td>
<td>0.12</td>
<td>0.18</td>
<td>0.24</td>
</tr>
</tbody>
</table>

2.5. Geology of the Exploration area

The intrusions mentioned above and all minor mafic intrusions are included in the First Quantum Minerals exploration project. Most of the geological and lithological study of the area is done by the company from various geophysical methods, geological mapping and borehole samples and a very few outcrops (Salo, 2013; Sproule, 2013; Määttä, 2013; Outhwaite, 2011). In each target, there are a big range of rock types which are unique in texture and visually discriminating the lithology is sometimes impossible.

Figure 5 Geological map of exploration area. (courtesy Geological survey of Finland)
Figure 5 show the main petrological units of exploration area. The mafic intrusions are mostly sill like and in some cases feeder dyke forms which intruded the Savukosky and Sodankylä formations. The intruded rocks consist of peridotite, olivine-pyroxenite and gabbro. The olivine-pyroxene rocks have common mineral characteristics which are named as Kevitsa-style. They have very high olivine (more than 70%), a pyroxene rich ground mass with additional phenocrysts of pyroxene. They also make a cumulate texture. Gabbros are medium to coarse grain, grey to greenish-grey colors consisting of generally equigranular pyroxene and feldspars. The amount of pyroxene in gabbro is very variable in each target.

Graphite rich schist (black schist) and phyllite are dominated in the area. Phyllites are sometimes mixed with quartzite. Other sedimentary rock types are mafic and intermediate tuff (Salo, 2013).

Various alterations occurred in the targets which only a few of them were studied in detail. Alteration in peridotites is minor serpentinization. Pyroxenites show some amphibole and/or chlorite alteration. There are evidences of hydrothermal mineralizations in many targets and Cu-Au anomalies were observed in the assay data. But PGE mineralizations are always orthomagmatic origin. Some of the contact rocks were metasomatised and formed a high Mg-Ca skarn. These rocks might have the same MgO content as ultramafic rocks but they can be easily distinguished by other non-compatible elements such as Cr (Outhwaite, 2011).
3. Discriminating methods

For exploration of magmatic intrusions with sulfide deposits, various exploration tools such as geophysics, remote sensing data or soil geochemistry are used. Glacier boulder tracing and deep till sampling are common in northern Scandinavia in order to find Ni mineralization. The exploration process then will be completed by geological mapping bed rock sampling and finally drilling.

Petrology of Nickel sulfide deposits is studied by various researchers. Ratio of rock forming elements can determine the proper magmatic environment of komatittes for Nickel sulfide deposits (Barnes S. J., 2004). Variation of Ni in olivine is an indicator for sulfide saturation of magma and Nickel concentration (Naldrett, 1989). This is a classical and practical method which is directly related to the genetic concept of Ni-Cu sulfide deposits.

While the exploration targets are getting deeper in the earth’s crust, the geophysical methods gets more popular for mine exploration. 2D and 3D reflection seismic methods are conventional methods for exploring deep-seated Ni-Cu sulfide ores (Milkereit, 2000).

The above listed methods are complicated and require expensive analytical methods such as REE and isotope analysis or scanning electronic microscope as well as lacking the precision. The method used in this study is based on the method developed by Lamberg (2005) and called as fertility analysis. The fertility analysis requires simple chemical analysis of rock forming and ore elements which can be obtain by XRF and ICP-MS. The method is a statistical tool which can discriminate barren and fertile deposits. It includes several steps, called screening parameters; each step is a statistical and logical analysis which is basically based on geological requirements for the formation of a sulfide nickel ore. The analysis indicates that a target passing all the steps shows evidence through geochemical features is has the sufficient geochemical evidence to be an economic Ni sulfide deposit.

The fertility analysis requires chemical data from rock forming elements Si, Al, Ca, K, Na, Ti, Fe, Mg and ore forming elements Ni, Cu, Co, S.

3.1. Ni# and Co#

Typically the variations of nickel, cobalt and copper content of sulfides are illustrated in Ni-Co-Cu ternary diagram. It provides a visual tool to compare different deposits but following the geological process in the diagrams is difficult. For that purpose, the ternary diagram is changed into X-Y diagram. The fertility analysis uses three elements but with derivatives called nickel and cobalt number. The Ni# describes the location of the point which is projected from Co corner to Ni-Cu side ((Equation 1). Co# describes the vertical distance from Ni-Cu side ((Equation 2). The formula is defined as below:

\[
Ni# = 100 \times \frac{Ni}{(Ni + Cu)} 
\]  \hspace{1cm} \text{(Equation 1)}

\[
Co# = 100 \times \frac{Co}{Ni + Co + Cu} 
\]  \hspace{1cm} \text{(Equation 2)}

The values of elements are in weight percent in the sulfide fraction. Ni# and Co# has no unit and the range of both of them are from 0 to 100.

Figure 6 shows the ternary and Ni#-Co# diagram of Sudbury data (Lightfoot, 2002)
Figure 6: Ternary diagram and Ni#-Co# diagram of Sudbury ore data.

Figure 7 summarizes how sulfide fractionation and segregation impacts on Ni# and Co#. Field 0 represents a system which has no sulfide fractionation. Basically it shows a chemical composition of a basaltic magma when it fractionates by silicate crystallization. A system which is only subjected to olivine fractionation makes a trend in field 1. Field 2 determines a chalcophile-depleted magma. This kind of magma had an early sulfide fractionation and the olivine fractionation is the only visible process in the graph. It is proved that early sulfide fractionation moves the trends towards higher Co# values. Fractionation of sulfides produces steep trends as shown in fields 3 and 4. The difference between field 3 and 4 is only the variation in the partition coefficients of Ni, Cu and Co in magma. Field 5 shows that magma had olivine segregation before sulfide fractionation. This magma is rich in Cu and depleted in Ni. It also shows low Ni#. Patterns 3, 4 and 5 are representative of sulfide fractionation. But field 6 is the pattern which is expected to be found in the intrusions which host sulfide accumulation.
3.2. Screening Parameters

The discrimination tool developed by Lamberg (2005) and used in this thesis follows the genetic concept of magmatic nickel sulfide deposits explained by Naldrett (1989). There are 4 requirements in order to produce a fertile sulfide deposit:

1. Magma should be primitive
2. A sulfide saturation process occurs
3. Sulfides interacts with a large amount of magma
4. Sulfides segregate and accumulate.

These requirements are studied in 7 steps; each one represents an analysis whether there are evidences that the physical process has taken place and the requirement is fulfilled (Figure 8). Instead of studying sample by sample, the fertility analysis considers a data set of a target. In each step a statistical-logical analysis is made for the sample set and received discrimination parameter is tested against the threshold values to decide whether this target has passed the step or has not. In order to remove the effect of high grade samples, they are removed in the data set and in addition the statistical analysis works with median and non-outlier data instead of mean and min or max. In the formulas presented below, Maxn and Minn represent the maximum non-outliner and minimum non-outliner values. The fertility analysis is designed to be an automatic process and work with a small number of samples (minimum 20 samples).
Figure 8 relationship between the requirements of the nickel sulfide ore formation and the discrimination parameters (Lamberg, 2005)

**Parameter 1. Primitive character of magma**

Nickel sulfide ores can only form from mantle driven magma. Based on (Equation 3 the maximum non-outliner of mafic index shows the primitiveness of magma. The target passes the test if Parameter 1 is greater than 60%.

\[ Parameter 1 = Max n_{\text{Mafic Index}} \]  
\[ \text{Range: 0 to 100} \]

**Parameter 2. Extend of sulfide saturation**

If at least 50% of samples contain at least 0.3% sulfides, the sulfide saturation of the target is considered as extensive. All the samples containing more than 0.3% sulfides are counted and it is divided by the total number of samples.

\[ Parameter 2 = 100 \times \frac{N_{\text{Sulfide>0.3\%}}}{N_{\text{All}}} \]  
\[ \text{Range: 0 to 100} \]

The result should be more than 50% to pass the steps 2.

**Parameter 3. Nickel rich, chalcophile undepleted magma.**

As mentioned before, high Co# shows the magma has been depleted in chalcophile elements. Parameter 3 is the minimum non-outliner value of Co# (equation 5). It should be less than 10 to pass the step.
Parameter 3 = \text{Minn}_\text{Co#} \quad \text{(Equation 5)}

Range: 0 to 100

**Parameter 4. Equilibration of sulfides with magma**

If sulfides interacted with all of the magma the Co# should be similar in all the data. For this purpose, first the data is divided into two groups of sulfide-rich and sulfide-poor based on sulfide median value. Parameter 4 is the median of Co# of sulfide-poor data subtracted from median of Co# of sulfide-rich data ((Equation 6). Parameter 4 should be less than -1 to pass.

\[
\text{Parameter 4} = \text{Median Co#}_{\text{Sulphide-poor}} - \text{Median Co#}_{\text{Sulphide-rich}} \quad \text{(Equation 6)}
\]

Range: -100 to 100

**Parameter 5. Coeval primitivity**

This parameter represents the primitiveness of sulfides within the MgO rich cumulates. The concept of this parameter is that good quality ore can form in the intrusion only if the very first magma pulse entering the intrusion is the most primitive, and non-depleted with base metals. The data is divided into two groups of MgO-rich and MgO-poor based on MgO mean value. Parameter 5 is calculated by subtracting median Co# of MgO-poor data from median Co# of MgO-rich data (Equation 7).

\[
\text{Parameter 5} = \text{Median Co#}_{MgO-poor} - \text{Median Co#}_{MgO-rich} \quad \text{(Equation 7)}
\]

This parameter should be more than -1 to pass.

Range: -100 to 100

**Parameter 6. Accumulation of sulfides**

The theory behind this parameter is that Ni sulfide ore can only form if segregated sulfides accumulate to form a concentrated mass. The sulfide droplets in the magma chamber are significantly denser than the magma and they sink down if there is the favorable condition and also olivine is the first mineral which is formed after that. So MgO (the representative of olivine) in comparison with sulfides can be a accumulation indicator. In practice, parameter 6 is calculated by subtracting the median sulfide content of MgO-rich samples (the same classification as the previous parameter) from the median sulfide content of MgO-poor samples (Equation 8).

\[
\text{Parameter 6} = \text{Median Sulphides}_{MgO-rich} - \text{Median Sulphides}_{MgO-poor} \quad \text{(Equation 8)}
\]

The positive value of the parameter passes the test.

Range: -100 to 100
Parameter 7. Fractionation or mobilization of sulfides

Mobilization of sulfides makes a wide variation of Ni# in low Co#. The same concept is used in parameter 7. First all the data with Co# lower than 6 is collected, then the parameter is calculated by subtracting max non-outlier of Ni# from min non-outlier of Ni# as shown in (Equation 9).

\[ Parameter\ 7 = \text{Maxn}\ \text{Ni#}_{\text{Co#}<6} - \text{Minn}\ \text{Ni#}_{\text{Co#}>6} \]  \hspace{1cm} \text{(Equation 9)}

Range: 0 to 100

If the result is more than 35, the target passes the test. But if the target fails this test, it is still counted as potentially economic target and more sampling is required for this purpose.

3.3. Overall Discrimination Value

Overall Discrimination Value consists of digit number ranging from 0 to 7 showing the last step passed by the target and a one decimal number ranges from 0.1 to 0.9 that shows how close it failed the last test. Eq 10 calculates the OD value, Step is the number of last step passed, S is the value of the first failed screening parameter, P is the passing criteria of the failed step and Max is the maximum range of the step.

\[ \text{OD} = \text{Step} + 0.499 \times \frac{S - P}{\text{Max} - P} \]  \hspace{1cm} \text{(Equation 10)}

3.4. Fertility analysis on Svecofennian intrusions of Finland

Lamberg (2005) tested the fertility analysis on 353 targets of Svecofennian intrusions, most of them belonging to Pori-Vammala-Kymäkoski belt in southwest and Parikkala-Kotalahi and Sulkava-Juva belt in east of Finland. Most of the intrusions outside of the belts failed the first test and have an OD value of zero.

Almost all the targets were primitive magma and about 77% of the targets show extensive sulfide saturation and 11 percent got OD value 6. Table 2 summarizes the fertility analysis of the targets.

The exploited Ni-Cu ores displayed OD values of 4 or higher with average of 5.88. The OD average of the sub-economic intrusions is 5.01 and barren intrusions are 2.97.

<table>
<thead>
<tr>
<th>Step</th>
<th>Passing %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Primitiveness</td>
<td>90.1</td>
</tr>
<tr>
<td>2. Sulfide saturation</td>
<td>77.0</td>
</tr>
<tr>
<td>3. Chalcophile undepleted magma</td>
<td>53.8</td>
</tr>
<tr>
<td>4. Equilibration of sulfide with magma</td>
<td>23.2</td>
</tr>
<tr>
<td>5. Coeval primitiveness</td>
<td>19.2</td>
</tr>
<tr>
<td>6. Accumulation of sulfides</td>
<td>11.3</td>
</tr>
<tr>
<td>7. Mobilization of sulfides</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Test with Svecofennian intrusions shows that method picks up relatively well the mined intrusions, and there is only one clear failure. Method was further tested with data sets from Thompson Nickel Belt,
Canada and Cape Smith komatiite belt in Canada. In both cases the fertility analysis showed higher OD value for the mineralized areas than for the barren areas.

4. Sampling and Analysis method
For this study drillhole and grab samples collected from 29 targets by First Quantum minerals were included. The targets are from Keivitsa mine and exploration projects around it. Table 3 shows the target names, drillholes and grab samples for each target.

All of the samples had been analysed by ALS Chemex with analytical methods ME-MS61 multielemental analysis with near-total digestion and ICP-MS for 48 elements, PGM-ICP23 for precious metals and ME-XRF06 as XRF analysis. Overlimit analyses (>1%) for Cu and Ni have been carried out with OG-46, ICP-AES method with aqua-regia digestion, analytical package. Overlimited analyses (>10%) for S have been done by S-IR08. From the total 6647 samples, only 791 samples were analyzed by XRF method and data for Si exits only for these data.

Table 3 Target names and number of drill hole (BH) and grab (Grab) samples

<table>
<thead>
<tr>
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4.1. Modeling of silicate content

A total of 5855 samples analyzed by ICPXS were dissolved by 4 acids solutions. This dissolution method only partially dissolves the samples and usually it can’t be used for Si analysis (or sometimes Al). The comparison of Al between XRF and ICPMS method is given in Table 4. Al analysis in XRF and ICPMS has less than 1% difference and this shows that complete dissolution occurred for Al.

A linear multi-variance regression modeling was done on the data with available SiO₂ analysis and it showed that SiO₂ has high correlation with Mg, Fe, Al, Ca and Na. The linear multi-variant model of SiO₂ is calculated with (Equation 11):

\[ \text{SiO}_2 = -0.65 \times Mg - 0.73 \times Fe - 0.24 \times Al + 0.21 \times Ca + 0.31 \times Na + 57.94 \]  

(Equation 11)

Calculated SiO₂ values show less than 5% error compared to the analyzed values. This is acceptable in technical application of data (Table 4).

Table 4 statistic data of Al and Si

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<th>Relative Error, %</th>
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<td>SiO₂</td>
<td>791</td>
<td>2.51</td>
<td>43.2</td>
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4.2. Calculation of exploration indexes with HSC software

HSC Geochemistry software is designed and developed by Outotec Company and it can handle thermodynamic calculations, chemical reactions and equilibrations. It has several modules which only HSC Geo and HSC Data is used for this thesis. HSC Geo provides mineralogical calculations and calculates the necessary fractions of the samples listed below:

- Sulfide fraction composition, Volatile free and volatile and sulfide free composition
- Mineral composition based on CIPW method
- Ni# and Co#
- Classify the elements for further chemical calculations

HSC Data provide statistic tools for modeling and plotting the data and population analysis. The screening parameters were calculated by a script written in HSC Data module (Lamberg & Tommiska, 2009).

4.3. Filtering the ultramafic samples

In order to use fertility analysis, first the mafic-ultramafic rock types should be filter out all the other rock types. Figure 9 shows the Mg-Cr values which classified the rock types. There are two lithology classes which bring error to the further steps. The first group is the mafic-ultramafic sediments with high Mg and other metal concentration. The second group is host rocks that have undergone variable intensity of Ca-Mg metasomatism and are called skarns. All lithologies classified in these two groups are depleted in metals.

In Figure 9, the sediments and metasomatized rocks are clearly discriminated from igneous rocks. Target Ponostama shows a different trend with lower Cr content than other targets. Mg is assumed to be a simple representative of mafi-ultramafic rocks. A detailed assay and logging of target Ponostama, the mean Mg
value of gabbroic and pyroxenite rocks were determined as 6.9 and 9.0 wt% respectively. Based on this study, all data with Mg less than 7% wt% was removed. And for not considering high Mg-Ca metasomatized rock, all samples with Cr<500ppm were removed. There are a small group of samples with higher Mg than the main trend. These samples are ferro-gabbros which are included in mafic-ultramafic group. The result of filtering is shown in Figure 12 as Ni#-Cu# graph. Total number of 3753 samples passes the test and was recognized as ultramafic rock types.

Figure 9 Mg-Cr diagram of all data. The lines show Cr=500 and Mg=8

Filtering the data made clearer Ni#-Cu# trend which now shows only the real data. Figure 10 shows the Ni#-Cu# graph discriminated by Cr and Mg values. There are two trends in raw data; the data with higher Cu# are sedimentary samples with no specific explanation for a magmatic intrusion. The total numbers of ultramafic samples of each target is given in Appendix 1.

The normative minerals calculated by CIPW method shows that majority of samples are ultramafics (Figure 11). A few numbers of samples are dunite and the number of gabbroic samples is very low due to high Mg filtering.
In Ni#-Co# target Ponostama shows a higher Co# and lower Ni#. Non-outliner range of Co# in Ponostama is 13-27 with the average of 20, but in other targets maximum Co# is less than 15 with the average of less than 12 (Figure 12). The samples for Kevitsa mine are also located in the main trend with low Co# and very high Ni#.
Figure 12 Ni# - Co# diagram for ultramafic samples. Hallow squares are Ponostama targets only
5. Interpretation of data

The fertility analysis was done for 21 exploration targets of FQM data. Figure 13 shows the overall discrimination value for all the targets. Except for the Kevitsa mine, only one target gets the highest possible OD value of 7, but three targets get OD value very close to 7. More than half of the targets have the OD between 1 and 2.

![Graph showing OD values for FQM exploration targets](image)

**Figure 13 OD values of FQM exploration targets. Targets with less than 25 sample numbers are marked with star (*)**

The value for each screening parameter is shown in Figure 14a to g. The intruding magma was very primitive and rich in Ni and chalcophile elements. Figure 14a shows all the target passes the primitiveness test with the range of 80 to 100. Also in Figure 14c, all the targets which have the sufficient valid data passed the test. Target Ponostama had early olivine crystallization and it is depleted in chalcophile elements. The studies of Ni content in olivines in Kevitsa mine suggest that the magma was unexpectedly high in Ni (Yang, 2013).

This target also has high Co# so it was expected to fail the tests related to the properties of magma. Therefore it failed the third screening parameter. Ponostama is located in the same formation as Kevitsa intrusion but far away from it and the petrology is very different from Kevitsa. In addition, both Figure 9 and Figure 12 show the magma which formed Ponostama intrusion is more evolved.
Figure 14(a to d) Screening Parameters for all targets. Red line shows the pass criteria of each Parameter.
Low values for Parameter 2 of all targets shows that extend of sulfide saturation of magma were very limited. The low sulfide content is caused by either low sulfate content of magma or limited contamination of magma by host rock.

In parameters 2, 3 and 7, there are no results for 5 targets because there were not available samples for these screening parameters. Sampling for Tarpoma, Kiima, Keikkuma and Ylaliesi were very limited and
most of them were grab samples. Outcrop samples are more susceptible for weathering and sulfides weather faster.

With a more careful look at Ni#-Cu# graph, it is possible to discriminate the intrusions into three groups in Figure 16. The first group has very high Ni# with the range 95-100 and low Co# with range 3-13 which show an intrusion with a komatiitic-picritic composition. Komatites have high concentration of chalcophile elements and low Ni/Cu value (Barnes S., 2006). The second group has Ni# with the range 80-95 and Co# with narrower range of 7-10 which shows an intrusion with a tholeitic composition. The third group shows a trend which indicates segregation of sulfide liquid. It starts with primary composition with Ni# ca 85 and Co# ca 8 and continues towards the origin up to Ni# 30 and Co# close to zero.

![Graph showing three groups of exploration targets](Image)

Figure 16 Ni#-Co# of exploration targets divided into three groups. Group I tholeiitic magma, Group II picrite magma, Group III sulfide segregation of magma. Two arrows show the path for sulfide segregation.

The group 3 in the graph shows the effects of sulfides in the mineralization. Lamberg (2005) showed that evolution trend of sulfide liquid in silicate melts makes the trend III with an orientation toward zero point. Any fertile target should have samples within this area that shows a sulfide segregation occurred in the area, Figure 17 shows the Ni#-Co# of the three targets with highest OD value. The samples for Puijärvi 1 and 2 and KSC64 are in group 1 or 2 and in the data in group 3 were spread all the way from high Ni# to low Ni# (Figure 17). This show that complete sulfide segregation occurred in Puijärvi intrusion. But a low OD value target such as Ruos 5 has no sample in group 3. All the other targets which have no data in group 3 also failed the test.

Field reports of targets also prove the fertility analysis. All Puijärvi targets and KSC64 showed minor Ni# mineralization in core logging. It should be consider that the fertility analysis removes the ore samples before analyzing the data. Puijärvi intrusion shows various Ni mineralization contacts in peridotites and olivine-pyroxenite. In addition, the structural interpretation of the target shows an overprint of hydrothermal Cu-Au on Puijärvi 1.
All the targets starting with the name KSC belongs to the southern part of Satovaara. KSC52, KSC53 and KSC64 are drilled through volcanic sediment, gabbro and peridotite but KSC33 is drilled through peridotite rocks. The high OD value of KSC52, 53, 64 supports the idea that the Ni mineralization of Satovaara intrusion is supposed to be in gabbroic formation. This is the opposite situation for Kevitsa mine which is located in olivine-pyroxenite. KSC69 also has high OD but it doesn’t have enough samples.

5.1. Comparing with Svecofennian mafic-ultramafic intrusions of Finland

The OD values of exploration targets are summarized in Table 5.

Table 5 testing results of exploration targets. OD numbers refer to the targets which passed the specific criterion, N passing and % Passing refer to the number and percentage of targets passed the step.

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<th>N Passing</th>
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</tr>
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<tr>
<td>2. Sulfide saturation</td>
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</tr>
<tr>
<td>3. Chalcophile undepleted magma</td>
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<td>7</td>
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<tr>
<td>4. Equilibration of sulfide with magma</td>
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<td>6</td>
<td>28.5</td>
</tr>
<tr>
<td>5. Coeval primitiveness</td>
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<td>28.5</td>
</tr>
<tr>
<td>6. Accumulation of sulfides</td>
<td>3</td>
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<td>23.8</td>
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<tr>
<td>7. Mobilization of sulfides</td>
<td>2</td>
<td>2</td>
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</table>
As mentioned in this chapter, only 38 percent of targets passed the second step and this is the only difference between exploration targets and intrusions of Finland. Svecofennian intrusions of Finland show high primitiveness and the magma was rich in chalcophile elements which is similar to the exploration targets. The exploited intrusions of Finland have average value 5.88 which is very low comparing with Kevitsa. But in the FQM exploration data there is only one target under mining therefore the comparison with exploited intrusions of Finland is not possible.
6. Discussion
There are only a few attempts to discriminate Ni-Cu orthomagmatic deposits and the fertility analysis is the one of the most recent one. All of the proposed methods are based on the theory proposed and developed by Naldrett (2004).

Barnes et al. (2004) studied the lithogeochemical properties of komattitic intrusions. The study was based on main and trace elements but they assay data should be corrected for alteration and metamorphism processes and some of the results were not able to discriminate between mineralized and barren targets. Also the discrimination methods are not quantitative.

Analyzing the Ni content of olivine is the direct method to prove the mineralization. This method is used by various researchers (Barnes S. J., 2004; Lightfoot, 2002; Lesher, 2001). This is a direct method that shows the characteristics of Ni in contact with sulfide and silicate phase. But unaltered silicate samples are very rare and the measuring methods such as SEM electron-microscope are more expensive than ICP analysis.

The fertility analysis studies the evolution of trace elements’ concentration during the evolution of magma. Therefore it is possible to determine the evolution of magma in each step. The elements chosen in this method are immobile but in case of multiple magma injection or extreme alteration, the results might be inaccurate.

Applying the test on various intrusions proves the validity of the test. The results from First Quantum Minerals can be compared to the results from Lamberg’s study. They all match the explanation in the study and they are proven by field studies.

For the final conclusion, the fertility analysis makes clear results with quantitative explanation, but other aspects of geology study such as field studies and mineralogy should be considered beside this method.
7. Conclusion

Two methods were introduced and tested on FQM exploration targets. All targets are magmatic intrusions of Kevitsa type intruded in Sodankylä and Savukoski formations, studies by geophysical methods, drilling and hand sampling. The confirmed age available is the Kevitsa intrusion in 2.05 Ga. The methods are Ni#-Co# graph and fertility analysis which require fewer sampling and cheaper analysis in order to get result. These methods determined the characteristics of magma and ranked the targets; the results of both prove each other and correlate with field data.

The main conclusions drawn from Ni#-Co# graph of exploration targets are the following:

- The magma which formed Kevitsa intrusion and other minor intrusions of age 2.04-2.2 Ga is mantle driven and rich in chalcophile elements. Target Ponostama is derived from a more evolved magma and it is depleted in Ni.
- The intrusions are mixed in komatitic and picritic magma. Targets Keikkuma, Mukkajarvi and Perura are formed from komatitic magma and all Sattovaara targets, all Puijärvi targets, all Ruosselka targets, Peura, and Rooki are formed from picritic magma. Kevitsa intrusion and KSC64 show a mixture of both magma types.
- The intrusions have very low sulfur content and only targets of Sattovaara, Puijärvi and Rooki show a sulfide segregation trend which is very important in Ni mineralization.

The main conclusion drawn from fertility analysis of exploration targets are the following:

- The fertility analysis worked fine on all targets and showed precise values for all targets. The test is independent of numbers of sample but the sampling should be extensive and derived from all parts of the intrusion. In this case study, the targets with only hand sampling showed low or zero OD value. Grab samples are not a representative of the entire intrusion and also sulfides weathers faster on the surface samples.
- The magma had very low sulfide content and the sulfur in host rock was not sufficient to make extensive sulfide saturation. Hence Ni is correlated with silicates (both olivine and pyroxene).
- The fertility analysis also ranked the targets by OD value. Targets with proven mineralization got the OD value 6.5-7. Targets of Puijärvi got OD 7 and the gabbroic part of Sattovaara got OD 6.0.

As the final conclusion, the fertility analysis is strongly recommended for the Kevitsa style intrusions of Northern Finland.
8. Acknowledgment

I would like to thank my supervisor Pertti Lamberg and Terhi Salo for all their help with the project and their comments and reviews of the text.

Many of my thanks goes to First Quantum Minerals for funding this project and the staff of the FQM exploration office providing me with the samples, geochemical data and technical consultation.
9. References


## 10. Appendix

Table 6 Final sample numbers of all targets

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Ni#-Co# of exploration targets: