GIS-based spatial assessment of Au, Ni and Cu-Zn exploration conducted in Central Finnish Lapland

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Abstract

The objective of this Master’s project was to produce a statistical dataset on orogenic gold, magmatic nickel-copper sulfide and volcanogenic massive sulfide copper-zinc exploration performed in Finnish Central Lapland over the past 20 years and to produce a time series of areas covered by Au, Ni, Cu and Zn exploration tenements. Secondly, the aim was also to give an overview on the mining history and to create a raster intensity map of already found ore in the study area and to spatially compare this to pre-existing mineral potential maps. The study area in question is defined by the GovAda project and a considerable part of its bedrock is composed of volcanic and sedimentary rocks belonging to the Central Lapland greenstone belt. This work is mainly based on a database of exploration tenements of Finland obtained from the Finnish Safety and Chemical Agency, the Fennoscandian Ore Deposit Database, and information on historic and current mine areas and their production. The preliminary data manipulation was primarily conducted using ArcGIS in conjunction with MS Excel, and resulted in total of 1938 claims to work with.

The results show that the exploration ‘boom’ in the study area has been ongoing since 2003 and that the metal prices and the amount of investment can be used as a reliable predictor of change in areas of active exploration tenements mainly for orogenic gold. In the case of magmatic Ni-Cu, the independent variables are more unstable and therefore are not as reliable. For the VMS type, it was impossible to produce a time series and calculate correlations due to the fact that there have only been 3 exploration tenements granted towards VMS exploration during the time period of interest. Based on spatial comparison of the raster intensity maps, locations of exploration tenements and mineral potential maps, the already known deposits are all located mainly in areas of high mineral potential and it would seem that most of mineral exploration has been also carried out in these high prospectivity areas.

Out of the 19 known deposits in the study area, only two have been discovered since 1995. There are two mines currently in operation and mining volumes have been rising every year since 2012 and are expected to rise even more in the future. Also, the future for mineral exploration looks brighter as the investments and drilling activities have recently shown signs of recovery.
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1 INTRODUCTION

Raw materials are fundamental to Europe’s economy, growth and jobs and they are essential for maintaining and improving our quality of life. Securing reliable, sustainable and undistorted access of certain raw materials is of growing concern within the EU and across the globe (European Commission, 2014). In 2008, the European Commission launched a program called the Raw Material Initiative, which originally included a list of 41 economically valuable raw materials for the EU. In the Raw Material Initiative, nickel and zinc have been labeled as economically very important raw materials for the EU and copper and gold as economically important even though they have not been categorized as critical materials (European Commission, 2008). Of the global supply of these four metals, EU’s share is currently <1% for gold, <3% for nickel, and <10% for copper and zinc. In the future, EU’s goal is to become more materially independent (European Commission, 2014).

Prior to 1995, the year when Finland joined the EU, there were no foreign major exploration companies operating in Finland, but the membership of the European Economic Area (EEA) enabled them to begin exploration and mining activities on Finnish soil in 1995. In 2011, Finland adopted a new mining act, which substituted the outdated mining legislation from 1965, in order to further the mining industry and organize the areas used for it and exploration in a socially, economically and ecologically sustainable manner (Finlex, 2011).

This thesis deals with GIS-based spatial assessment of Au, Ni and Cu-Zn exploration conducted in Central Finnish Lapland in the past 20 years. The topic was provided by the Geological Survey of Finland (GTK) and the study was carried out within the framework of the GovAda project (Governing adaptive change towards sustainable economy in the Arctic) funded by the Academy of Finland. The general objective of the GovAda project is to develop and test the scenario methodology of mining and integrated assessment of ecological, economic and social values of alternative land uses in the chosen study area (Kivinen et al. 2015).
The study area is located in Central Lapland of Finland (Fig. 1) and it covers an area of 14,380 km\(^2\) in total, stretching mainly over the areas of three municipalities: Sodankylä, Kittilä, and Kolari. Minor parts of the Muonio, Pelkosenniemi, and Savukoski municipalities are also included. The considered time period of mineral exploration and mining in the study area begins in 1995. The aim of this thesis is to create a statistical dataset on orogenic gold, magmatic nickel-copper sulfide and volcanogenic massive sulfide (VMS) copper-zinc exploration performed in Finnish Central Lapland over the past 20 years and to produce a time series of areas covered by Au, Ni, Cu, and Zn exploration tenements in Central Lapland. Furthermore, the aim is also to give an overview on the mining history of the area and provide statistical information on the annual excavated ore tonnages and production volumes by commodity. Using ArcGIS, the distribution of the known deposits and areas already explored are then spatially compared with pre-existing mineral potential maps. Mineral prospectivity analyses have already been done for orogenic gold, magmatic nickel-copper sulfide and VMS-type deposits in the Central Lapland greenstone belt (Nykänen et al. 2011, 2014, V. Nykänen, pers. comm. 2016) and thus these ore types were chosen to be the focus of this thesis.
2 MINING, EXPLORATION AND MINERAL STRATEGY IN FINLAND

Finland has a relatively long mining history beginning in the 16\textsuperscript{th} century (Puustinen 2003, Haapala & Papunen 2015), and during the past few decades, foreign major exploration and mining companies have shown a growing interest towards the Finnish mining and exploration scene (e.g., Tuusjärvi et al. 2014). Finland offers a favorable investment and operating environment for the exploration industry with notable potential for new discoveries as several commodities yet remain underexplored. The Geological Survey of Finland (GTK) provides quantitative assessments of undiscovered resources for multiple commodities and ore types, including orogenic gold deposits, VMS deposits and Ni-Cu deposits (Rasilainen et al. 2012, 2014, Eilu et al. 2015). In the Fraser Institute’s survey of mining companies (Jackson & Green 2016), Finland was ranked the fifth most attractive country for exploration and mining companies in 2015 and has been among the top ten for the past five years. This ranking is based on the geologic attractiveness and government policy (regulations, taxation, and infrastructure) towards exploration investment. Finland has a good infrastructure, Finnish soil and bedrock are well mapped, and excellent geological and geophysical databases are readily available free of charge for all interested parties (GTK 2016). All this contributes to the fact that the exploration and mining industry has experienced a new boom in Finland since the turn of the millennia: mineral exploration has been active, new mining projects have been initiated and investments have increased (Laukkonen & Törmä 2014).

A change in minerals policy has been seen in Europe in the past ten years or so, which also affected Finland on a national level. In 2008, the Raw Materials Initiative was adopted by the European Commission and one of its core targets is to secure sustainable supply of non-energy and non-agricultural raw materials within the EU by increasing self-sufficiency and access to them through global markets and recycling (European Commission 2008). The Raw Materials Initiative sparked a national-level initiative in Finland, Finland’s Mineral Strategy (2010), where the vision for 2050 is that Finland is a global leader in the sustainable utilization of mineral resources and the minerals sector is one of the key foundations of the Finnish national economy. Also, in 2011, Tekes (the Finnish Funding Agency for Innovation and Technology) launched the Green Mining Program in an attempt to actually make Finland into a forerunner of responsible mining
globally by 2020. Tekes has been the biggest funder in Finnish mineral industry research and development and has taken part in 65% of the projects, whereas the EU has funded one fifth of the ventures (Kokko 2014).

In June 2011, a new mining act came into effect with an objective to promote mining and organize the use of areas required for it, and further exploration in a socially, economically, and ecologically sustainable manner (Finlex 2011). Simultaneously, the Finnish Safety and Chemical Agency (Tukes) became the new exploration and mining permitting authority in Finland and currently upholds the mining registry as well. As a result of the renewal of the mining legislation, the terminology was updated. Some outdated terms were decommissioned and the terms reservation (varaus) and exploration permit (malminetsintälupa) are currently in use. Under the old mining act, the size of a single exploration license was limited to 1 km², and they were valid for a maximum of 5 years, instead of the current 4 years for exploration permits. On its website, Tukes provides an estimate of 120 days for the expected processing time for exploration permits for a timberland area, 365 days for a Natura area and 730 days for a Sami area. The processing of a mining permit is currently expected to take from 90 to 180 days. Prior to 2011, the upcoming transition to a new, more restrictive mining act created a surge of new exploration permit applications in the following years (Table 1) and for example, Yleisradio (the Finnish broadcasting company, YLE 2012) reported that the processing of a single permit in 2012 may have even taken two and a half years. This caused a backlog in the permit handling, which was finally relieved in 2014 when, in the case of the study area, 544 exploration permits were granted.
3 GEOLOGY OF THE STUDY AREA

Finland is part of the Fennoscandian Shield, which is composed almost entirely of Precambrian rocks. Geologically, the study area is located on the Archean Karelian craton (Fig. 2) and a considerable part of its bedrock is composed of volcanic and sedimentary rocks, which belong to the Central Lapland greenstone belt (CLGB) (Hanski & Huhma 2005).

**FIGURE 2.** Extent of the Central Lapland Greenstone belt and some other main geological units in the northern part of the Fennoscandian Shield. The location of the study area outlined by a thick green line. Modified after Niiranen et al. (2014).
Melezhik & Hanski (2012) describe the early Paleoproterozoic evolution of Fennoscandia between 2505-1900 Ma, consisting of two main stages of southwest-prograding intraplate rifting leading to fragmentation of the shield and eventually to oceanic crust development, closure of ocean basins, continent-arc collisions and resultant orogenies. This evolution and the cratonization of the Archean bedrock are well observed in Finnish Lapland (Vaasjoki et al. 2005). The supracrustal rocks of the CLGB can be divided into two main units: the predominant Karelian 2440-2000 Ma rift-related metamorphosed volcano-sedimentary rocks on top of the Archean basement and the less abundant 1890-1770 Ma Svecofennian sequence (e.g., Hanski & Huhma, 2005; Niiranen et al. 2015). Furthermore, the supracrustal rocks were originally divided by Lehtonen et al. (1998) into 7 distinct lithostratigraphic units, which are discussed later in this thesis. The CLGB is part of one of the largest known Paleoproterozoic supracrustal belts in the world, the CLGB, spanning nearly uninterrupted from northern Norway through Finland to Russian Karelia (Niiranen et al. 2014), where several exploitable ore deposits, such as Suurikuusikko in Kittilä, have been found and several are under exploration.

The CLGB is bounded by the arc-shaped Lapland granulite belt in the northeast and the Central Lapland granite complex in the south (Hanski & Huhma 2005). The geological evolution of Finnish Lapland can be condensed in three main stages: 1) the formation of the Archean cratonic basement, 2) deposition of Paleoproterozoic volcano-sedimentary cover and associated intrusive magmatism at 2500-1920 Ma, when mantle plume-related komatiitic to rhyolitic lavas were erupted, and 3) the 1930-1910 Ma Lapland-Kola and 1930-1770 Ma Svecofennian orogenic events deforming the bedrock (Vaasjoki et al. 2005, Hanski 2015).

The core zone of the study area, including the Kittilä group and the northwestern part of the Sodankylä group (Fig. 3), have mainly undergone greenschist facies metamorphism but when moving a bit more to the south, the degree of regional metamorphism increases rapidly to amphibolite facies. In the northern and northeastern direction from the core area, the transition is from lower metamorphic grades to upper amphibolite and eventually to granulite facies upon reaching the Lapland granulite belt (Hölttä et al. 2007).
The complex Paleoproterozoic evolution of more than 500 Ma and subsequent extensive deformation and hydrothermal activity and regional metamorphism created favorable conditions for the formation of ore deposits. The eastern and middle portion of the CLGB contains abundant mafic-ultramafic layered intrusions aged between 2440-2050 Ma, which host economically significant ore deposits, such as Kevitsa (Vaasjoki et al. 2005). Figure 3 shows known orogenic gold, magmatic Ni-Cu-PGE sulfide and VMS deposits and prospects. Most of the known deposits and prospects in the study area fall into the orogenic gold type and the majority of them are located in the proximity of the Sirkka thrust zone and Kiistala shear zone. Prospects are displayed based on their main commodity: copper, gold, or zinc.

**FIGURE 3.** General geology, lithostratigraphic groups and known orogenic gold, magmatic nickel-copper sulfide and VMS deposits of the study area. STZ = Sirkka thrust zone, KSZ = Kiistala shear zone. Source: Based on DigiKP, the digital bedrock map database of GTK (2016) (http://gtkdata.gtk.fi/Kalliopera/index.html) and Fennoscandian Ore Deposit Database (Eilu et al. 2016).
3.1 Lithostratigraphic Units

Based on the studies of the Lapland Volcanite project in the 1980s and 1990s, a lithostratigraphic classification of the supracrustal rocks of the CLGB was introduced by Lehtonen et al. (1998). Since then, the stratigraphy has been examined further and the lithostratigraphic units partly revised (e.g., Niiranen et al. 2015). The CLGB is divided into seven group-level units (Fig. 4) based on their age, geological relationships, rock types and geochemical composition. The general descriptions of the these lithostratigraphic units in this section are based on Lehtonen et al. (1998) together with the updates by Hanski & Huhma (2005) and Niiranen et al. (2015).

FIGURE 4. Lithostratigraphic units of the CLGB and the main age groups of mafic-ultramafic intrusions within. Modified from Niiranen et al. 2015.
3.1.1 Vuojärvi Group

The Vuojärvi Group, the lowest unit in the stratigraphy, is characterized by quartz-feldspar-sericite schists and gneisses, which are located at the southern margin of the CLGB (Niiranen et al. 2015) (Fig. 3). The precise age of the Vuojärvi Group is still unknown.

3.1.2 Salla Group

The Salla Group rocks occur in the eastern part of the study area and can be found in the vicinity of the ~2440 Ma Koitelainen layered intrusion (Fig. 3), for instance, where volcanic rocks of the Salla Group are cut by this intrusion. U-Pb zircon dating suggests that the Salla Group rocks are roughly coeval with the Koitelainen intrusion (Manninen et al. 2001). The rocks are dominantly volcanic in origin and vary from basaltic andesite to rhyolite in composition (SiO$_2$ 54-70 wt.%), with more evolved varieties occurring generally higher in the stratigraphy. They were emplaced on the rifted Archean basement and the lack of intervening epiclastic rocks indicate that eruptions occurred quickly under subaerial conditions (Hanski & Huhma 2005). The primary minerals in the Salla Group rocks have been replaced due to greenschist facies metamorphism but the original volcanic structures of these extrusive rocks are well-preserved in some places.

3.1.3 Kuusamo Group

The rocks of the Kuusamo Group (Onkamo Group of Lehtonen et al. 1998) were deposited either on the lavas of the Vuojärvi or Salla Groups or directly on the Archean gneisses and granites. These extensive mafic volcanic rocks are tholeiitic and komatiitic in nature.

3.1.4 Sodankylä Group

After the magmatic episode that formed the underlying groups, a thick, epiclastic sedimentary sequence formed on top of the Achaean gneisses or the older units of the CLGB (Lehtonen et al. 1998, Hanski & Huhma 2005). The Sodankylä Group sedimentary rocks are widespread and dominantly represented by orthoquartzites, sericite quartzites, and mica schists, but also minor carbonate rocks with some stromatolitic structures and tholeiitic basalts and basaltic andesites occur. A minimum age for the volcanic rocks is provided by ~2200 Ma mafic differentiated sills cutting the quartzites (Fig. 4) of the Sodankylä Group but not reaching into the overlying
litostratigraphic units (Hanski & Huhma 2005). Fuchsite is a characteristic mineral of the sericite quartzites and commonly stains the rock with tints of green. The abundance and distribution of quartzites suggest that the depositional basin was markedly widened from a relatively narrow rift basin after the previous volcanic phases terminated. Primary structures include cross-bedding, graded bedding, herringbone structures and mud cracks, indicating a tidal environment (Lehtonen et al. 1998).

3.1.5 Savukoski Group

The contact between the Sodankylä and Savukoski Groups is gradual, indicating gradual deepening and further rifting of the depositional basin. The Savukoski Group consists of a very heterogeneous collection of rock types: fine-grained metasedimentary rocks, including phyllites and black schists, some dolomites and mafic tuffites as well (Lehtonen et al. 1998). It contains the first manifestations of graphite- and sulfide-bearing schists in the Paleoproterozoic stratigraphy of the CLGB. A minimum age of ca. 2060 Ma for these rocks is provided by the crosscutting Keivitsa intrusion (Mutonen & Huhma 2001). The pelitic metasediments are overlain by komatiitic and picritic rocks, which were derived from a magnesian parental magma containing ≥20 wt.% MgO (Hanski et al. 2001). Komatiitic and picritic volcanic rocks occur both as pillowed and massive lavas, pillow breccias, and multiple types of volcaniclastic rocks including agglomerates, lapilli, and reworked tuffs, and despite being heavily altered, exhibit well-preserved primary structures. The Sirkka thrust zone, at the southern margin of the Kittilä greenstone area, is one of the most altered regions of the CLGB where komatiitic rocks of the Sodankylä Group have been intensely carbonatized. This, for instance, is a good area for gold exploration (Hanski & Huhma 2005).

3.1.6 Kittilä Group

The Kittilä Group, also known as the Kittilä greenstone complex, is the most extensive of the seven lithostratigraphic units in the CLGB, covering an area of more than 2600 km² (Hanski & Huhma 2005) and presently reaching a vertical thickness of 9 km (Niiranen 2015). In the area of the Kittilä town, this folded volcanic complex is a wide and relatively flat-lying and weakly deformed, but becomes a narrower and steeply E-dipping tectonized zone towards the north. This is probably due to the overthrusting of the Lapland Granulite belt from the northeast (Hanski & Huhma 2005). Also the contacts of the Kittilä Group rocks with the older units seem to be tectonic. Metavolcanic rocks dominate the Kittilä Group, but several types of sedimentary
interbeds and larger units can also be found. These are metagraywackes, phyllites, graphite- and sulfide-bearing schists and some carbonate rocks. Banded iron formation (BIF) units can also be found. An age of ca. 2015 Ma has been obtained for crosscutting felsic porphyries of the Kittilä Group. Field observations suggest that the felsic porphyries are coeval with the mafic volcanic and subvolcanic rocks and hence, the U-Pb zircon data on felsic rocks have important bearings on the age of the whole Kittilä Group (Rastas et al. 2001). The Kittilä Group is subdivided into four lithostratigraphic type formations, which are from oldest to youngest: Kautoselkä (Fe-tholeiitic volcanic rocks), Porkonen (BIF, Fe-sulfide bearing phyllites and schists), Vesmajärvi (Mg-tholeiitic volcanic rocks), and Pyhäjärvi (sedimentary schists) (Lehtonen et al. 1998,). The large Suurikuusikko orogenic gold deposit is hosted by the Kittilä Group rocks, representing the good ore potential of this stratigraphic group (Niiranen et al. 2015).

3.1.7 Kumpu Group

Many high fells of Central Lapland, such as Ylläs, Aakenustunturi and Levi, are composed of Kumpu Group rocks. This group represents the youngest stratigraphical unit of the CLGB and is the only one belonging to the 1890-1770 Ma Svecofennian sequence (Lehtonen et al. 1998). Its deposition postdates 1880 Ma (Rastas et al. 2001, Hanski & Huhma), and there is a major stratigraphic break between this coarse-clastic molasse-like metasediment-dominated sequence and the underlying older Karelian stratigraphic units. The Kumpu Group forms a thick sedimentary unit, which comprises meta-arkoses, quartzites, polymictic conglomerates with greywacke interbeds, and siltstones. A widespread hematite pigment gives the rocks a characteristic reddish brown or even a purple tint. The observed sedimentological features suggest that deposition took place in fluvial environments, such as alluvial fans and braided river deposits (Kortelainen 1983).
3.2 MAFIC-ULTRAMAFIC INTRUSIONS

Several layered mafic intrusions and dike swarms can be found in the CLGB. They are generally divided into three main age groups (Fig. 4): 2440 Ma intrusions, 2200 Ma differentiated sills, and 2050 Ma intrusions (Hanski & Huhma 2005). When the Archean orogenic movements ceased, crustal-scale faulting with associated volcanic activity and formation of sedimentary basins occurred within the eroding and peneplaning Archean crust (Vaasjoki et al. 2005) and this lead to emplacement of 2440 Ma Koitelainen intrusion in the eastern CLGB, for example. The Koitelainen intrusion was injected into the contact zone of the Archean basement and overlying Paleoproterozoic volcanic rocks of the Salla and Vuojärvi Groups. The 2220 Ma differentiated sills can be found in the Sodankylä Group quartzites, in an area between Sodankylä and Kittilä towns, where a string of intrusive bodies run close to the southern margin of the CLGB. The 2220 Ma magmatic stage seems to have been short-lived and the intrusions are not known to host any significant mineral deposits. Mafic intrusions with an age of ca. 2050 Ma are common in northern Finland and in the CLGB they can be found especially within the Savukoski Group. The Kevitsa-Satovaara complex is the only representative of a sizeable mafic-ultramafic body of this age group and the Kevitsa copper-nickel deposit (Mutanen 1997) is discussed further in the next chapter.
4 MINERAL DEPOSIT TYPES OF THE STUDY AREA

On a global scale, greenstone belts are well endowed with certain metal ore deposits, such as iron in banded iron formations (BIF), nickel and copper in komatiites, gold in orogenic gold deposits, and copper-zinc in volcanogenic massive sulfides (VMS). Of these, BIF are not well developed in the greenstone belts in Finland and only form thin layers between volcanic rocks or mica schists (Hanski 2015). VMS deposits are also rare within Finnish greenstone belts but a handful of minor VMS-style base metal occurrences have been found in the southern part of the CLGB. The majority of the known deposits and occurrences in the study area are of the orogenic gold type, but there has been a growing interest towards magmatic Ni-Cu exploration in the recent years. The Kolari region in the western CLGB contains several iron oxide copper-gold deposits (IOCG) and a few deposits hosting energy metals, industrial minerals, and semi-precious gemstones have been discovered in the study area as well.

In this section, each of the three chosen mineral deposit types, orogenic gold, magmatic nickel-copper sulfide and VMS, and their genesis are briefly introduced with an example from the CLGB. The locations of the chosen deposits are shown in Fig. 1. Suurikuusikko in Kittilä represents the orogenic gold type, Kevitsa in Sodankylä is an example of magmatic Ni-Cu sulfide deposits in layered intrusions, and Pahtavuoma exemplifies the general traits of a VMS deposit.

4.1 MAGMATIC NICKEL-COPPER SULFIDE DEPOSITS

According to Naldrett (2010), magmatic Ni-Cu sulfide deposits in mafic-ultramafic rocks can be divided into two main groups based on their sulfide content and whether they are enriched in Ni and Cu or PGE. Sulfide-rich deposits with >10% sulfides are explored for because of their Ni and Cu, whereas certain sulfide-poor deposits with <5% sulfides are valued primarily for their PGE. Magmatic Ni-Cu sulfide deposits have a spatial relationship with cratonic boundaries and they can also be found in proximity of coeval large igneous provinces. Most of them are related to a mantle plume activity and occur in intracontinental settings or in passive margins at the edge of small marginal basins (Begg et al. 2010). In a generalized model of Begg et al. (2010), fluxes
of mantle-derived, mafic-ultramafic magma plumes rise beneath a >150-km-thick lithosphere, where they cause medium- to high-degrees of partial melting, releasing Ni from olivine. These large volumes of melt are later channelized and start to rise through trans-lithospheric faults and reach the crust at cratonic margins where they interact with crustal rocks resulting in crustal assimilation.

Changing compressional-extensional tectonic environments focus and locally enhance the magma flow, and the sulfur required to form the majority of the deposits is derived from abundant S-rich crustal rocks (Barnes & Lightfoot 2005). The assimilation of sulfur-bearing sediments, such as black shale and paragneiss, which are found in the proximity of the majority of these deposits, is thought to bring about sulfide saturation. The sulfide liquid then collects the chalcophile metals, but is not deposited until the magma flow slows down enough for sulfide droplets to precipitate within structural straps, such as lava channels and magma conduits (Maier & Groves 2011). Occasionally, new magma might be injected into the intrusion before the sulfide liquid has solidified and transport it to a new depositional site. Tectonic activity and deformation can displace the sulfides from their parent bodies and form brecciated deposits (Barnes & Lightfoot 2005). The igneous bodies hosting magmatic Ni-Cu deposits tend to be irregular and small, tens to hundreds of meters in width and height, and often difficult to locate (Maier & Groves 2011).

In Central Lapland, the ca. 2050 Ma the Kevitsa layered intrusion is the best known example of magmatic Ni-Cu sulfide deposits in the study area. Ultramafic intrusive rocks are widespread within the CLGB and occur at multiple stratigraphic levels, with the Savukoski Group being the most prominent host for a magmatic deposit (Hanski & Huhma 2005). According to Santaguida et al. (2015), the Kevitsa intrusion was emplaced during rifting in an intracontinental setting. The Keivitsa magma intruded into the sedimentary pile at about the level where the amounts of sulfides and graphite increase (Mutanen 1997).

The funnel-shaped Kevitsa intrusion can be described as a composite ultramafic olivine-pyroxenite to gabbroic intrusion (Fig. 5). Based on drill-hole data, the Kevitsa intrusion has a thickness of more than 1.5 km and the deposit geometry at this depth reflects the effects of regional deformation and original magmatic emplacement relationships.
(Santaguida et al. 2015). The intrusion has been divided stratigraphically into the marginal chill zone, ultramafic zone, gabbroic zone, and granophyre (Mutanen 1997). The marginal chill zone is less than 10 m thick at the lower contact of the intrusion and consists of microgabbro, quartz gabbro, and quartz-rich pyroxenite. The more than 1-km-thick ultramafic zone acts as the host for the Keivitsansarvi Cu-Ni-PGE deposit and is characterized by olivine pyroxenite and websterite. The overlying gabbroic zone is on average 500 m thick and grades rapidly into the granophyre (Mutanen 1997).

After its emplacement, the Kevitsa intrusion has undergone greenschist-facies metamorphism and hydrothermal alteration. The predominant alteration styles are serpentinization, amphibolitization and epidotization (Le Vaillant et al. 2016).

The Keivitsansarvi ore body (Fig. 5) comprises mainly disseminated sulfides and the main ore minerals are pentlandite and chalcopyrite, which occur together with pyrrhotite and magnetite (Santaguida et al. 2015). Globally, this is an unusual characteristic as disseminated deposits are commonly not economic unless they have been significantly upgraded during metamorphism (Barnes & Lightfoot 2005). The ore body is irregular in shape and concentrated in the center of the intrusion (Santaguida et al. 2015) rather than along the basal contact where the mineralized rock is most commonly located (Barnes & Lightfoot 2005).

Two main types of ore are distinguished based on their Ni and PGE tenors (Mutanen 1997). They are called the “normal” and “Ni-PGE” type. The normal ore occurs as a series of continuous bodies, representing about 95% of the economic resource. It is characterized by 2-6 vol.% of sulfides, has Ni and Cu grades of of 0.3 wt.% and 0.4 wt.%, respectively, and a Ni tenor of 4-7 wt.% The sulfide content in the Ni-PGE ore is similar, but the Ni grades tend to be much higher, Cu grades lower and it has an extremely Ni tenor in the range of 15-40 wt.% (Mutanen 1997, Yang et al. 2013). Also a pyrrhotite-rich mineralization called “false ore” has been identified, having a low Ni tenor of 0.3-4 wt% (Mutanen 1997). Sulfides with a low Ni/Cu ratio have generally been associated with a low-MgO magma (Naldrett 2010), and the parental magma for the Kevitsa deposit has been thought to be basaltic rather than komatiitic or picritic in nature (Mutanen 1997, Hanski & Huhma 2005).
4.2 VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

The volcanogenic massive sulfide (VMS) deposits are a broad group of deposit types that were formed throughout the history of Earth and are mainly mined for their Cu and Zn content, but also for Pb, Au and Ag. These deposits form in volcanically active extensional tectonic settings, at mid-ocean ridges, in oceanic volcanic arcs and in extensional back-arc basins, and there is a general consensus that submarine venting is
the process responsible for the formation of most of the discovered VMS deposits on Earth (Robb 2005, Pirajno 2009).

The VMS deposits form at, or near (<3 km below seafloor), the seafloor through focused discharge of hot, metal-rich hydrothermal fluids and the immediate host rocks can be either volcanic or sedimentary (Galley et al. 2007). Most VMS deposits, but not all, occur in clusters and have two major attributes. Firstly, they are typically mound-shaped to tabular, stratabound bodies, which are mostly composed of massive (>40%) sulfide, quartz and minor phyllosilicates, and iron-oxide minerals and altered silicate wall-rock. Secondly, they are underlain by discordant to semi-concordant stockwork veins and disseminated sulfides. Also, these stockwork veins are surrounded by distinctive alteration haloes, which might reach the hanging-wall strata above the VMS deposit (Galley et al. 2007).

The best-known analogues for the formation of VMS ore deposits are black smokers on the modern ocean floor, which vent high temperature (350-400°C), highly reduced hydrothermal fluids mobilized by an underlying heat source (typically a magma chamber). These hydrothermal fluids are mainly derived from sea water, but may also have minor magmatic fluid components, and precipitate metals as sulfide or oxide mineralization. The main source of metals is thought to be the rocks through which the sea water percolated. The discharged fluid retreats back into the crust through a network of small fractures and is circulated again, creating a hydrothermal system (Pirajno 2009, Tornos et al. 2015). The massive sulfide mounds can grow up to be several tens of meters high and several hundreds of meters wide, being composed of an inner zone of chalcopyrite and pyrite followed by sphalerite and galena with Mg-rich silicates, carbonates, anhydrite, barite and variable amounts of amorphous silica (Tornos et al. 2015).

The volcanogenic massive sulfide deposits are grouped according to their base metal and gold content and host-rock lithology, but the classification where the deposits are divided into Cu-Zn, Zn-Cu and Zn-Pb-Cu groups based on the ratios of these metals, is used most commonly (Galley et al. 2007).
To date, only one of clearly VMS-type deposit has been identified from the study area. The Pahtavuoma deposit was discovered in 1970 and the brief description of the main characteristics given here is mainly based on Inkinen (1979). The Pahtavuoma deposit is hosted by a sedimentary formation, which contains graphite-bearing phyllites and mica schists that correlate with the metasediments hosting the Kevitsa Ni-Cu-bearing intrusion (Hanski 2015). Four separate low-grade and relatively small copper ore bodies and six zinc showings (+ three U occurrences) occurring in the sedimentary schists have been discovered so far (Inkinen 1979). The copper showings are hosted within several different rock types, such as graphite-bearing phyllites and micaceous schists but also, to lesser extent, schistose metagraywackes and albite schists. As depicted in Fig. 6, the copper mineralization is typically found at the southern edge of a schist unit in close contact with greenstones, where some zinc also occurs at the margins of the copper showings. The zinc mineralization alone is not necessarily in close contact with
greenstones as it has also been found further north in separate schist zones, being hosted mainly by phyllites. The predominant mineral association in the copper mineralization is chalcopyrite-pyrrhotite and in the zinc showings, pyrrhotite-sphalerite-ilmenite. In the area of the zinc mineralization, the ore minerals may fill cracks in breccia together with carbonate minerals and quartz (Inkinen 1979). It is suggested that the appearance of ore-forming fluids and mineralization processes in the Pahtavuoma area were related to volcanic eruptions in the W-E-trending sedimentary basin during the final stage of the greenstone volcanism. The CLGB underwent further rifting and deepening of the depositional basin during the formation of the Savukoski Group around 2060 Ma and this was the most favorable time for the formation of VMS deposits as well (Inkinen 1979).

4.3 OROGENIC GOLD

Orogenic gold deposits are characterized by their contemporaneity with large deformational events driven by accretionary or collisional orogenies of all ages (Goldfarb et al. 2005). Several models for the source of fluids and metals in orogenic gold settings have been proposed but a metamorphic devolatilization model by Phillips and Powell (2010) is often regarded as the most viable model explaining the majority of the orogenic gold provinces. Prograde metamorphism and deformation leads to breakdown of volatile-bearing minerals, such as chlorite, carbonate minerals, and pyrite, liberating metals and hydrothermal fluid from the source rock, and they also drive long-distance migration of fluids through crustal structures (Goldfarb & Groves 2015). Gold is transported dominantly as a reduced sulfur complex in low-salinity, near-neutral, H₂O-CO₂±H₂S-bearing fluids, where CH₄ is also sometimes present (Phillips & Powell 2010). Mineralization is controlled by second- or third-order structures, such as faults, shear zones, fracture arrays, stockworks, or breccia zones, near large-scale compressional bodies (Groves et al. 1998, Goldfarb et al. 2005). Pressure changes during seismic events precipitate gold in quartz veins, whereas fluid-wallrock interactions are responsible for depositing gold adjacent to the veins (Eilu 2015). The fluid-wallrock interactions bring about hydrothermal alteration and the width of alteration haloes can vary from a few centimeters around a single vein to several kilometers when enveloping a major deposit. Among the typical alteration styles in
Orogenic gold deposits are carbonatization, sericitization, and sulfidization (Groves et al. 1998, Goldfarb et al. 2005). Carbonate minerals include ankerite, dolomite, or calcite; sulfides include pyrite, pyrrhotite, or arsenopyrite; alkali metasomatism involves sericitization and in some cases formation of fuchsite, biotite, or K-feldspar and albitization. Mafic minerals are replaced by carbonates and mica and intense sulfidization are found in Fe-rich rocks and BIF. Generally, orogenic gold deposits are quartz-dominant vein systems with ≤3-15% sulfide minerals and ≤5-15% carbonate minerals (Groves et al. 1998).

Orogenic gold mineralization can take place at crustal depths from 3 to 15 km, and the deposits can be hosted by a variety of greenstone belt-associated lithologies, including mafic volcanic rocks, metasediments, banded iron-formation, as well as felsic to intermediate intrusive rocks (Robb 2009). Orogenic gold can be found within host rocks which have been metamorphosed between greenschist and amphibolite facies conditions, with mineralization taking place at syn- to post-peak metamorphism at temperatures between 180-600 ºC and pressures of <1-5 kbar, indicating vertically extensive systems (Groves et al. 1998, Goldfarb & Groves 2015). Deposits have a down-plunge continuity of hundreds of meters to several kilometers and they are hosted in moderately to steeply plunging, tabular- to pipe-shaped rock volumes (Ridley & Diamond 2000).

Based on their metal endowment, the orogenic gold deposits can be divided into two sub-categories, “gold-only” and “anomalous metal association” (Goldfarb et al. 2005). Orogenic gold deposits with anomalous metal associations resemble typical orogenic deposits, but in addition to gold, they may also contain Ag, Cu, Co, Ni, or Sb as potential commodities (Eilu 2015). According to Eilu (2015) and Wyche et al. (2015), almost all of the CLGB gold occurrences can be placed into the orogenic gold category, even though they do exhibit some unusual characteristics, such as pre-gold base metal mineralization, albitization, and enrichment in Cu±Co±Ni, therefore they are called orogenic gold deposits with anomalous metal association to be precise.

The Suurikuusikko deposit is the largest gold producer in Europe and also the largest orogenic gold deposit of the CLGB (Wyche et al. 2015). It is occurs in the Kittilä Group and has been speculated to occur at the contact between the Kautoselkä and Vesmajärvi
Formations (Fig. 7), in a 50- to 200-m-thick transitional zone consisting of mafic tuff, graphitic sedimentary rock, and BIF, which correlates with the Porkonen Formation (Patison et al. 2007, Doucet et al. 2010, Wyche et al. 2015). The >25-km-long, N-S-trending Kiistala shear zone is the host structure to several mineralized bodies but five key auriferous zones have been the main focus of recent exploration in a 4.5-km-long section of the shear zone at Suurikuusikko (Doucet et al. 2010, Wyche et al. 2015). The ore bodies are 3- to 20-m-wide lenses, which may be hundreds of meters long, are nearly vertical, and run parallel to the Kiistala shear zone (Wyche et al. 2015). The Suurikuusikko deposit displays most of the common characteristics of an orogenic gold deposit. It has a strong structural control by a long lived-shear zone and the lithological control seems to be the pre-gold albitization, which rendered the host rocks more competent and conductive to fluid flow (Eilu 2016). Also the proximal alteration assemblages of albite-muscovite-dolomite or ankerite-quartz-rutile-arsenopyrite-pyrite reflect the presence of a typical orogenic fluid. This proximal alteration includes all ore, and the halo width varies from 10 m to 100 m. The distal alteration extends laterally from 100 m to even 300 m beyond the ore and proximal alteration (Wyche et al. 2015). Mineralized rocks at Suurikuusikko are brecciated and carbonate-quartz veined in varying degrees and display intensive albite alteration. In the gold zones, the average sulfide content is 10% with a range of 2-30% (Doucet et al. 2010). The majority of gold occurs within arsenopyrite (73.2%) and arsenian pyrite (22.7%), being almost exclusively refractory. The rest is found as native gold within pyrite and arsenopyrite grains (Doucet et al. 2010, Wyche et al. 2015). Using the Re-Os dating, gold-rich arsenopyrites have been dated at 1916 ± 16 Ma and an age correlation with the overthrusting of the Lapland Granulite belt, 1920-1900 Ma, has also been indicated. The current understanding is that the mineralization at Suurikuusikko took place 60-100 Ma after the Kittilä Group deposition and during regional metamorphic peak, contemporaneously with minor felsic intrusions (Wyche et al. 2015).
4.4 OTHER MINERAL DEPOSIT TYPES

In addition to the three mineral deposit types discussed above, the western part of the study area (Fig 1.) hosts more than 10 broadly similar iron oxide copper-gold deposits. The Kolari region has been known to host iron ore resources for centuries and three IOCG mines (Hannukainen, Juvakaisenmaa and Rautuvaara) have been in operation in the past (Puustinen 2003). None of these are active at the moment but the Hannukainen mining project is currently under permitting, feasibility study and test mining phase and might be reopened in the upcoming years (Hannukainen Mining Oy 2017). Between 2012 and 2015 Tukes did not receive any new exploration permit applications towards IOCG exploration in the study area.

The magnetite deposits in the Kolari area were formed along a major structural zone when local branches of the Bothnian megashear were reactivated and the inflow of hydrothermal saline fluids occurred. The fluids possibly originated from evaporates that were deposited earlier within an intracontinental rift zone between Norrbotten and Karelian cratons (Moilanen & Peltonen 2015). Niiranen et al. (2007) were the first to consider that the general features of the Kolari deposits display characteristics typical for IOCG occurrences and, based on U-Pb age data, suggested an age of ca. 1800 Ma for these ores.

Some paleoplacer gold occurrences have been identified in the Kumpu Group, the uppermost lithostratigraphic unit of the CLGB. The occurrences are hosted by both monomictic and polymictic, 30- to 60-m-thick conglomerate lenses deposited in deltaic and fluvial fan environments after around 1873 Ma and probably before 1770 Ma (Eilu 2015).

Apart from the before-mentioned deposit types, the study area also contains mineral deposits and metallogenic areas where energy metals (uranium), non-metallic industrial minerals (calcite), and semi-precious gemstones (amethyst) can be found. These are not addressed any further in this thesis, but can be viewed online in an interactive map service Mineral Deposits and Exploration (GTK 2016, available: http://gtkdata.gtk.fi/MDaE/index.html).
5 MATERIALS AND METHODS

A geologic map (Fig. 3) showing the general geology, distribution of the lithostratigraphic groups, the most important fault and shear zones and the locations of known mineral deposits in the study area was drawn using ArcGIS 10.3. The geological features, including the bedrock and structural lines, are based on the digital bedrock map database of the Geological Survey of Finland (GTK 2016) and the mineral deposits of the study area were taken from the Fennoscandian Ore Deposit Database (FODD, Eilu et al. 2016) by employing the geoprocessing tool called ‘clip’ in ArcGIS. The deposits were then classified based on their genetic type and marked on the bedrock map. The FODD only contains the deposits for which calculations on total ore tonnages have been done, leaving out all the prospects without resource or reserve estimates. The GTK provides an open online map service Mineral Deposits and Exploration (MDaE, available: http://en.gtk.fi/informationservices/map_services/, accessed 14.12.2016), from which the prospect data were extracted and exported to ArcGIS. The relevant prospects were then chosen and displayed on the map based on their main commodity.

This thesis also contains results of a GIS-based spatial assessment of Au, Ni-Cu and VMS-type Cu-Zn exploration conducted in Finnish Central Lapland. The original materials used include the database of exploration tenements of Finland (updated on April 1, 2016) obtained from the Finnish Safety and Chemical Agency (Tukes) and information on historic and current mine areas and their production data in Finland in the period of 1530-2001, as compiled by Puustinen (2003). From 2001 onwards, the updated mineral commodity production and mining volume data can be obtained from Tukes, which currently upholds the mining registry in Finland.

Pre-processing of the exploration tenement data was the most time-consuming part of the project. The first step was to extract the key components from the database, including all the historic exploration tenements in Finland since the 1940s. Filtering the relevant data from the large database was conducted in ArcGIS 10.3 first by clipping out all the exploration permits outside the study area and also excluding the permits that were expired before year 1995. Since the main focus of this work is on three ore types and their exploration and mining history, the data were furthermore divided into ore type categories. In their permit application, the exploration companies have to inform
the authorities which minerals or metals they are going to explore, and the division into different ore type categories was done utilizing this mineral exploration information in the database. If there was any ambiguity or difficulty in distinguishing the mineral or ore type to which the exploration was truly targeted, it was helpful in some cases to read the exploration reports if they were available. Some claims were even clarified by sending an email to trusted sources with first-hand information on which metals a certain company was interested in exploring for in the past. The ore type categories into which the data were divided were orogenic gold, magmatic nickel-copper sulfide deposits, and volcanogenic massive sulfide (VMS) copper-zinc deposits. These three ore types were selected because mineral potential maps covering the study area have already been compiled for these genetic mineral deposit types (Nykänen et al. 2011, 2014, V. Nykänen, pers. comm. 2016). A time series for the iron-oxide copper gold type (IOCG) was also constructed but is not discussed further in this thesis. All the permits that represented other ore types were removed. The result was a total of 1938 claims: 1016 claims in the orogenic gold category, 919 in the magmatic nickel-copper sulfide category, and only 3 in the VMS category.

After separating the exploration tenements relevant to this thesis from the rest of the data and dividing them by the genetic ore type, each type was furthermore subdivided into three permit categories based on their application, granted and expiration dates. These categories were ‘filed applications’, ‘granted permits’, and ‘active permits’. The number of applications was calculated for each year between 1995 and 2015 by giving each permit the value of ‘1’ and using the SUMIFS function in Excel to select permits with relevant attributes. The extent of the exploration area was also of interest, and this was calculated in the same manner. The results of this step are shown in Table 1, where the filed applications, granted permits, active permits, and exploration area of these permits are listed in total for all three ore types each year.

After the data manipulation presented above, it was possible to start making time series and testing correlations and possible causal relationships between different variables. There are a number of factors affecting the exploration and mining industry, which is changing and reforming on a global level. For example, a change in consumption patterns, emerging of new economies, such as China and India, globalization and rising awareness of environmental and social issues related to mining, climate change and the
notion of sustainable development have an effect on metal prices, costs of mining, and exploration budget trends. More national-level factors affecting the mining and exploration industry are legislation, permitting, taxation, and infrastructure.

**TABLE 1.** Orogenic Au, magmatic Ni-Cu sulfide and VMS exploration permit history in the study area in 1995-2015. Source: Exploration tenement database (Tukes 2016).

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of permits</th>
<th>Area (km²)</th>
<th>Number of permits</th>
<th>Area (km²)</th>
<th>Number of permits</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>135</td>
<td>113.13</td>
<td>104</td>
<td>79.18</td>
<td>165</td>
<td>124.24</td>
</tr>
<tr>
<td>1996</td>
<td>42</td>
<td>31.11</td>
<td>83</td>
<td>68.87</td>
<td>225</td>
<td>177.34</td>
</tr>
<tr>
<td>1997</td>
<td>13</td>
<td>10.66</td>
<td>18</td>
<td>14.11</td>
<td>209</td>
<td>169.34</td>
</tr>
<tr>
<td>1998</td>
<td>24</td>
<td>18.76</td>
<td>24</td>
<td>18.76</td>
<td>144</td>
<td>111.86</td>
</tr>
<tr>
<td>1999</td>
<td>22</td>
<td>13.61</td>
<td>11</td>
<td>5.92</td>
<td>88</td>
<td>62.59</td>
</tr>
<tr>
<td>2000</td>
<td>22</td>
<td>14.27</td>
<td>23</td>
<td>18.58</td>
<td>92</td>
<td>68.81</td>
</tr>
<tr>
<td>2001</td>
<td>40</td>
<td>30.84</td>
<td>37</td>
<td>25.52</td>
<td>116</td>
<td>87.7</td>
</tr>
<tr>
<td>2002</td>
<td>38</td>
<td>31.94</td>
<td>45</td>
<td>36.27</td>
<td>141</td>
<td>108.09</td>
</tr>
<tr>
<td>2003</td>
<td>99</td>
<td>83.32</td>
<td>68</td>
<td>53.62</td>
<td>202</td>
<td>157.47</td>
</tr>
<tr>
<td>2004</td>
<td>148</td>
<td>126.83</td>
<td>161</td>
<td>138.97</td>
<td>340</td>
<td>280.33</td>
</tr>
<tr>
<td>2005</td>
<td>126</td>
<td>113.03</td>
<td>117</td>
<td>102.97</td>
<td>424</td>
<td>355.15</td>
</tr>
<tr>
<td>2006</td>
<td>55</td>
<td>50.69</td>
<td>33</td>
<td>31.99</td>
<td>409</td>
<td>351.29</td>
</tr>
<tr>
<td>2007</td>
<td>155</td>
<td>141.86</td>
<td>47</td>
<td>43.08</td>
<td>413</td>
<td>357.71</td>
</tr>
<tr>
<td>2008</td>
<td>31</td>
<td>48.76</td>
<td>14</td>
<td>12.01</td>
<td>374</td>
<td>330.56</td>
</tr>
<tr>
<td>2009</td>
<td>283</td>
<td>254.97</td>
<td>138</td>
<td>124.13</td>
<td>434</td>
<td>382.54</td>
</tr>
<tr>
<td>2010</td>
<td>485</td>
<td>485.18</td>
<td>44</td>
<td>72.99</td>
<td>376</td>
<td>371.67</td>
</tr>
<tr>
<td>2011</td>
<td>47</td>
<td>135.52</td>
<td>11</td>
<td>65.5</td>
<td>277</td>
<td>338.77</td>
</tr>
<tr>
<td>2012</td>
<td>23</td>
<td>82.04</td>
<td>249</td>
<td>244.07</td>
<td>494</td>
<td>552.74</td>
</tr>
<tr>
<td>2013</td>
<td>22</td>
<td>301.04</td>
<td>83</td>
<td>138.2</td>
<td>533</td>
<td>560.76</td>
</tr>
<tr>
<td>2014</td>
<td>18</td>
<td>244.35</td>
<td>544</td>
<td>934.95</td>
<td>1049</td>
<td>1473.69</td>
</tr>
<tr>
<td>2015</td>
<td>11</td>
<td>105.57</td>
<td>23</td>
<td>215.07</td>
<td>935</td>
<td>1565.63</td>
</tr>
</tbody>
</table>

In this thesis, correlations were calculated for metal prices and investments in exploration in relation to the total area claimed for gold and nickel prospecting. The exploration budgets are typically shown by country and contain information on the investment trends by company size (junior, intermediate, major) and whether the investment is towards grassroots, late-stage & feasibility, or mine site exploration. Exploration budget trends in Finland for gold, copper and nickel were available in SNL Metals & Mining (http://www.snl.com/Sectors/MetalsMining/) from 1999 onwards. Since exploration for VMS has not been substantial in the study area, with only 3 permits having been granted towards VMS exploration during the period of interest, a
time series for this ore type alone was impossible to make. The metal prices were also derived from SNL Metals & Mining, representing the annual averages from 1995 to 2015.

Excel was utilized in calculating the dependencies between the chosen variables, which were metal prices, investments in exploration, and the total area claimed for gold and nickel prospecting each year (active permits). Values were plotted on scatter diagrams with a linear trend line and $R^2$ value, which is the coefficient of determination. The coefficient of determination is a key output of regression analysis. It is interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variable. Independent variables (metal price and exploration budgets) were plotted on the X axis and the presumably dependent variables on the Y axis. An $R^2$ value between 0 and 1 indicates the extent to which the dependent variable is predictable. An $R^2$ value of 0.10 means that 10% of the variance in Y can be explained by X, an $R^2$ value of 0.20 means that 20% can be explained, and so on (Gujarati & Porter 2009). After obtaining the $R^2$ values, p values were calculated by using the regression tool from the data analysis add-in in Excel. These are used to determine the statistical significance in a hypothesis test, meaning that they help to assess whether the independent variables are good predictors of changes in the dependent variables or not. Generally, 0.05 is used as the cut-off value for significance. If the p value is less than 0.05, we reject the null hypothesis that there is no difference between the means and conclude that a significant difference does exist (Sullivan 2014). If the p value is larger than 0.05, we cannot conclude that a significant difference exists. Metal prices and exploration budgets were also compared with the applied and granted permit numbers and their areas, but they gave generally a worse outcome than when compared with the area where exploration permits were active.

Puustinen (2003) published a historical overview on the mining industry in Finland with a special emphasis on the production volumes of different mineral products between 1530 and 2001. The mining data relevant to this thesis were compiled essentially from this work, but to gain more recent information, mineral exploration reports by the GTK, statistics on mineral deposits and mines (Tilastoja vuoriteollisuudesta 2011-2015) by Tukes, and mining data from SNL Metals & Mining were also utilized.
In the study area, seven mines, which represent all of the three ore types chosen for this thesis, have been in operation in the past and two of them are currently in operation (Fig. 1). For these seven mines, the statistical information, such as ore and wall-rock tonnages and production volumes, found from the above-mentioned sources, were tabulated and a time series for the mining data was compiled in the same manner as for the exploration permits.

The Fennoscandian Ore Deposit Database (FODD, Eilu et al. 2016) contains a large amount of data on ore deposits across the Fennoscandian Shield, including resource and reserve estimates and information on how much has been mined in the cases where a mine has been or is still in operation. This total tonnage (resources + reserves + mined) information and the locations of already known mineral deposits were a good starting point in the process of compiling a raster intensity map for the study area. The data were originally observable as point data in ArcGIS and did not exhibit a realistic view of the size of the area in which the metals have already been found. This meant that the cell size in the point data of the known deposits was much smaller than the actual deposits/targets and therefore needed to be enlarged. This was done firstly by choosing the exploration permits which had the same name (or some alternative name used for the deposit) with one of the known deposits and giving them the total tonnage value from the FODD in a new field created for this purpose. In some cases, where no exploration permits were found in the area of a known deposit, the value was given to cover an area of an active mining permit. The polygons, both exploration and mining permits, were then transformed into a raster form by using the polygon-to-raster conversion tool in ArcGIS and giving them a new cell size of 1000 (1 km x 1 km). These two rasters were then compiled to achieve the end product, a raster intensity map showing the already found metals of the study area.

Prospectivity maps (Fig. 8) for orogenic gold, nickel and VMS already exist and have been constructed by using spatial modelling techniques in ArcGIS (Nykänen et al. 2011, 2014, V. Nykänen, pers. comm. 2016). These techniques can be divided into two main groups based on the amount of available information. The groups are data and knowledge driven. A conceptual-fuzzy logic model is knowledge driven and is generally used when there are not many known deposits in the modelled area, whereas in the mature mineral exploration terrains where abundant data and known mineral deposits exist a data-driven approach is more suitable (Nykänen 2008).
Figure 8. Workflow and components involved in creating a mineral prospectivity map (Nykänen 2008).

Finnish soil and bedrock are well mapped, and Finland has excellent geological and geophysical databases (GTK 2016, http://en.gtk.fi/mineral_resources/exploration.html). However, the study area does not host many known Ni-Cu or VMS deposits (Eilu et al. 2016) and therefore the spatial analysis methods are generally more knowledge than data driven. The knowledge-driven methods are based on expert opinions and in the fuzzy approach, the values for the evidential datasets, expressed on a continuous scale from 0 to 1, are chosen based on the subjective judgment of an expert (Nykänen et al. 2014). The raw data for mineral potential maps in the case of the Central Lapland Greenstone belt (CLGB) were derived from high-resolution airborne geophysics, regional gravity information, regional till geochemistry, and small-scale bedrock maps (Nykänen 2008). The knowledge of general characteristics of a certain ore type and
locations of already known deposits help to build and train the mineral potential model further. For example, several known occurrences of orogenic gold are found within the CLGB (Eilu et al. 2016) and the key parameters used to describe this ore type in the model were low magnetic and resistivity responses, high gravity gradient, anomalous As, Au, Cu, Fe, Ni and Te in till, proximity to tectonic structures (Sirkka shear zone), paleostress anomaly and proximity to greenstone/sedimentary contacts (Nykänen 2008). A mineral potential map for orogenic gold was then constructed by applying a hybrid of data- and knowledge-driven models. These pre-existing prospectivity maps were layered with the raster intensity map of already known deposits in ArcGIS, making the spatial comparison of these two possible. A common workflow and components used in constructing a prospectivity map is shown in Fig. 8 and fully explained in Nykänen (2008).
6 MINING AND MINERAL EXPLORATION HISTORY OF THE STUDY AREA

6.1 MINERAL EXPLORATION

Between 1995 and 2015, in total 1938 exploration permits targeting to orogenic gold, magmatic nickel and copper, and VMS copper-zinc were approved in the study area. Of these, 1016 permits were filed towards gold exploration, 919 towards magmatic nickel and copper, and only 3 towards VMS copper-zinc. Exploration work has been carried out in an area of 1969.21 km², which makes up about 13.7% of the total study area of 14380 km². To calculate this number, all overlapping areas were dissolved into one and the permit areas that have been active more than once during 1995-2015 were only taken into account once. The Nature conservation and Natura 2000 areas occupy approximately 4455.96 km² of the land area, which is 31% of the study area where exploration permits are not generally granted.

![Exploration permit history of CLGB 1995-2015](image)

**FIGURE 9.** Time series of the annual exploration permit history of the study area in 1995-2015, showing the number of filed applications, granted permits per year, and the number of exploration permits active each year. Source: Tukes.

Figure 9 shows the trends in the amounts of the applications filed, permits granted, and permits active per year. The number of the filed applications and granted permits stayed approximately at the same level until 2009 and 2010, when the number of applications drastically exceeded the number of permits granted. This possibly reflected the
suspicion and expectations related to the new mining act, which came into effect in 2011. This surge in applications caused a backlog in the permit handling, which was finally relieved in 2014 when 544 new exploration permits were granted (Table 1). According to an overview on the current mineral and mining industry by the permitting authority (Tukes), there is currently no backlog in the exploration and mining permit handling (Liikamaa 2016). There has been a lot of talk and coverage in the media about the mining boom in Finland in the 21st century, and YLE, for example, reported in the beginning of 2015 that the mining and exploration industry in Finland is showing signs of fading due to the decrease in commodity prices. The mining boom in Finland is argued to have lasted from 2008 to 2012, when seven new mines were opened, two of which are located in the study area, and when the number of filed exploration permit applications was very high (YLE 2015). For our study area, it could be said that the mining boom (or rather the exploration boom) has been ongoing since year 2003, when the number of active exploration permits in the area exceeded 200 and has not decreased below this number since then.

In Table 2, the companies that have explored the study area since 1995 are listed in an alphabetical order. The table shows the size of the company, number of granted permits, the deposit type and commodities they were after, the total area of exploration, and the years during which the permits have been active. The company size and parent company information was drawn mainly from SNL Metals & Mining (http://www.snl.com) but also from annual company reports and Kauppalehti company search (in Finnish: http://www.kauppalehti.fi/5/i/yritykset/yrityshaku/). In a classification by SNL Metals & Mining, the exploration and mining companies are divided into three categories primarily by company’s adjusted annual revenue. Junior companies have limited revenues, <$50 million, and mainly include pure explorers and aspiring producers, which have not yet reached the intermediate-company threshold. Intermediate-level companies have an annual nonferrous revenue in the range of $50-500 million. A company is considered to be major when its adjusted nonferrous mining-related revenue exceeds $500 million and it has the financial strength to develop a major mine on its own. In the study area, exploration has been undertaken by 43 companies, of which the vast majority, 29 companies, were junior in size.
TABLE 2. Companies in alphabetical order which have conducted exploration in the study area during 1995-2015. Sources: Exploration tenements (Tukes), SNL Metals & Mining, Kauppalehti company search.

<table>
<thead>
<tr>
<th>Permit holder</th>
<th>Company size</th>
<th>Parent Company / Corporate HQ</th>
<th>Number of permits</th>
<th>Deposit types</th>
<th>Commodities</th>
<th>Area, km²</th>
<th>Years permits active</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA Sakatti Mining Oy</td>
<td>Major</td>
<td>Anglo American / United Kingdom</td>
<td>544</td>
<td>Magmatic Ni</td>
<td>Ni, Cu, PGE, (Cu)</td>
<td>720.30</td>
<td>2012-2019</td>
</tr>
<tr>
<td>Agnico-Eagle AB</td>
<td>Major</td>
<td>Agnico Eagle Mines Ltd / Canada</td>
<td>116</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>1.86</td>
<td>2014-2017</td>
</tr>
<tr>
<td>Agnico-Eagle Finland Oy</td>
<td>Major</td>
<td>Canada</td>
<td>208</td>
<td>Orogenic Au</td>
<td>Au, Cu, Zn, Pb</td>
<td>257.49</td>
<td>2010-2020</td>
</tr>
<tr>
<td>Anglo American Exploration B.V.</td>
<td>Major</td>
<td>United Kingdom</td>
<td>176</td>
<td>Magmatic Ni</td>
<td>Ni, Cu, Au</td>
<td>160.41</td>
<td>2004-2010</td>
</tr>
<tr>
<td>Aurion Resources Oy</td>
<td>Junior</td>
<td>Canada</td>
<td>3</td>
<td>Orogenic Au</td>
<td>Au, Ni, Zn, Cu, Pd, Pt, Ag, Pb</td>
<td>15.98</td>
<td>2014-2019</td>
</tr>
<tr>
<td>Belvedere Resources Finland Oy</td>
<td>Junior</td>
<td>Canada</td>
<td>5</td>
<td>Orogenic Au</td>
<td>Au, Cu, Co</td>
<td>4.27</td>
<td>2005-2011</td>
</tr>
<tr>
<td>BHP Billiton World Exploration Inc</td>
<td>Major</td>
<td>Canada</td>
<td>9</td>
<td>Magmatic Ni</td>
<td>Ni, Cu</td>
<td>9.01</td>
<td>2005-2010</td>
</tr>
<tr>
<td>Conroy Gold and Natural Resources</td>
<td>Junior</td>
<td>Ireland</td>
<td>9</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>7.95</td>
<td>2014-2019</td>
</tr>
<tr>
<td>Dragon Mining Oy</td>
<td>Intermediate</td>
<td>Australia</td>
<td>36</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>86.11</td>
<td>2012-2018</td>
</tr>
<tr>
<td>Endomines Oy</td>
<td>Junior</td>
<td>Endomines AB / Sweden</td>
<td>27</td>
<td>Orogenic Au</td>
<td>Au, Cu, Fe</td>
<td>25.44</td>
<td>2008-2016</td>
</tr>
<tr>
<td>Ezybonds (UK) Plc</td>
<td>Junior</td>
<td>United Kingdom</td>
<td>1</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>0.99</td>
<td>1997-2005</td>
</tr>
<tr>
<td>Finngold Resources PLC.</td>
<td>Junior</td>
<td>United Kingdom</td>
<td>1</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>0.99</td>
<td>1997-2001</td>
</tr>
<tr>
<td>FQM FinnEx Oy</td>
<td>Major</td>
<td>FQM Ltd / Canada</td>
<td>21</td>
<td>Magmatic Ni</td>
<td>Ni, Cu, Pt, PGE, Au, Co</td>
<td>244.85</td>
<td>2012-2019</td>
</tr>
<tr>
<td>FQM Kevitsa Mining Oy</td>
<td>Major</td>
<td>FQM Ltd / Canada</td>
<td>30</td>
<td>Magmatic Ni</td>
<td>Ni, Cu, Pt, PGE, Au, Co</td>
<td>27.09</td>
<td>2012-2015</td>
</tr>
<tr>
<td>Gold Mine Sitonen &amp; Saiho AY</td>
<td>Junior</td>
<td>Finland</td>
<td>2</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>0.20</td>
<td>2002-2013</td>
</tr>
<tr>
<td>Kevitsa Mining AB</td>
<td>Major</td>
<td>FQM Ltd / Canada</td>
<td>1</td>
<td>Magmatic Ni</td>
<td>Ni, Pt, Co, Au</td>
<td>1.06</td>
<td>2006-2011</td>
</tr>
<tr>
<td>Lapland Goldminers Oy</td>
<td>Junior</td>
<td>Sweden</td>
<td>12</td>
<td>Orogenic Au</td>
<td>Au, Cu, Ni</td>
<td>7.74</td>
<td>2005-2016</td>
</tr>
<tr>
<td>Magnus Minerals Oy</td>
<td>Junior</td>
<td>Finland</td>
<td>2</td>
<td>Magmatic Ni</td>
<td>Ni, Cu, Zn, Au, Ag, Co</td>
<td>19.00</td>
<td>2015-2020</td>
</tr>
<tr>
<td>Magnus Minerals Oy</td>
<td>Junior</td>
<td>Finland</td>
<td>1</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>0.14</td>
<td>2009-2014</td>
</tr>
<tr>
<td>Morenia Oy</td>
<td>Junior</td>
<td>Finland</td>
<td>1</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>0.31</td>
<td>2013-2016</td>
</tr>
<tr>
<td>Northern Lion Gold Oy</td>
<td>Junior</td>
<td>Canada</td>
<td>6</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>4.31</td>
<td>2005-2010</td>
</tr>
<tr>
<td>Northland Exploration Finland Oy</td>
<td>Junior</td>
<td>Northland Resources S.A / Lux</td>
<td>4</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>93.28</td>
<td>2010-2012</td>
</tr>
</tbody>
</table>
## TABLE 2. Continued.

<table>
<thead>
<tr>
<th>Permit holder</th>
<th>Company size</th>
<th>Parent Company / Corporate HQ</th>
<th>Number of permits</th>
<th>Deposit types</th>
<th>Commodities</th>
<th>Area, km²</th>
<th>Years permits active</th>
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</thead>
<tbody>
<tr>
<td>Northland Resources Ab</td>
<td>Junior</td>
<td>Northland Resources S.A / LUX</td>
<td>14</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>12.22</td>
<td>2005-2010</td>
</tr>
<tr>
<td>Onas Resources Oy</td>
<td>Junior</td>
<td>Finland</td>
<td>1</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>0.03</td>
<td>1993-1998</td>
</tr>
<tr>
<td>Outokumpu Metals &amp; Resources Oy</td>
<td>Intermediate</td>
<td>Finland</td>
<td>50</td>
<td>Magmatic Ni</td>
<td>Ni</td>
<td>45.30</td>
<td>1993-1998</td>
</tr>
<tr>
<td>Outokumpu Mining Oy</td>
<td>Intermediate</td>
<td>Finland</td>
<td>5</td>
<td>Magmatic Ni</td>
<td>Ni, Cu</td>
<td>2.93</td>
<td>1995-1998</td>
</tr>
<tr>
<td>Outokumpu Oy</td>
<td>Intermediate</td>
<td>Finland</td>
<td>26</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>13.83</td>
<td>1991-2005</td>
</tr>
<tr>
<td>Polar Mining Oy</td>
<td>Intermediate</td>
<td>Dragon Mining Ltd / Australia</td>
<td>105</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>99.36</td>
<td>2000-2015</td>
</tr>
<tr>
<td>Riddarhyttan Resources Ab</td>
<td>Junior</td>
<td>Sweden</td>
<td>10</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>8.04</td>
<td>1995-2005</td>
</tr>
<tr>
<td>Sakumpu Exploration Oy</td>
<td>Junior</td>
<td>S2 Resources Ltd / Australia</td>
<td>1</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>1.59</td>
<td>2015-2020</td>
</tr>
<tr>
<td>ScanMining Ab</td>
<td>Junior</td>
<td>Sweden</td>
<td>21</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>18.73</td>
<td>1998-2010</td>
</tr>
<tr>
<td>ScanMining Oy</td>
<td>Junior</td>
<td>Sweden</td>
<td>16</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>13.16</td>
<td>2004-2013</td>
</tr>
<tr>
<td>Siitonen Asser</td>
<td>Junior</td>
<td>Finland</td>
<td>3</td>
<td>Magmatic Ni</td>
<td>Ni, Co, Au</td>
<td>0.15</td>
<td>1996-2000</td>
</tr>
<tr>
<td>Sodankylän Malminetsintä Oy</td>
<td>Junior</td>
<td>Finland</td>
<td>1</td>
<td>Magmatic Ni</td>
<td>Ni, Cu, Pd, Pt, In, Ir, Rh, Rb, Ru</td>
<td>111.68</td>
<td>2014-2018</td>
</tr>
<tr>
<td>Svenska Platina AB</td>
<td>Junior</td>
<td>Riddarhyttan Resources Ab / Sweden</td>
<td>89</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>68.30</td>
<td>2001-2006</td>
</tr>
<tr>
<td>Tailtiu Oy</td>
<td>Junior</td>
<td>Taranis Resources Inc / Canada</td>
<td>38</td>
<td>Orogenic Au</td>
<td>Au, Cu</td>
<td>34.22</td>
<td>2001-2019</td>
</tr>
<tr>
<td>Terra Mining Oy</td>
<td>Junior</td>
<td>Terra mining Ab / Sweden</td>
<td>41</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>36.04</td>
<td>1992-2001</td>
</tr>
<tr>
<td>Trans-International Mineral Expl</td>
<td>Junior</td>
<td>Conroy Gold and Natural Resources Plc / Ireland</td>
<td>9</td>
<td>Orogenic Au</td>
<td>Au</td>
<td>5.12</td>
<td>2004-2009</td>
</tr>
</tbody>
</table>
However, 1189 of the permits were filed by major exploration and mining companies, which are all of foreign origin. The first foreign companies to emerge and start exploration in the study area, alongside Finnish Outokumpu and GTK, were from Sweden, Ireland, and the United Kingdom in the late 1990s.

After the turn of the millennium, companies from outside Europe became more interested in the Finnish mineral resources, and the first major companies began their exploration through subsidiary companies based in Finland or Sweden. Most of the exploration companies operating in the study area today have parent companies which are primarily based in Canada, but also in Australia and the United Kingdom.

One of these companies is AA Sakatti Mining Oy, which has by far the largest number of exploration permits under its belt. AA Sakatti Mining Oy filed 113 exploration applications in 2009 and 415 applications in 2010 towards nickel, copper and PGE exploration, which alone accounts for the huge increase in permit applications during these years. The Sakatti deposit was defined as a potentially large deposit (Eilu et al. 2016), and definitive estimates of resources or reserves have only recently (March, 2017) been published by Anglo American.

Active gold exploration in Central Lapland started after the discovery of the Saattopora deposit in 1985 (Niiranen 2015), and the amount of new exploration permits every year since 1995 has varied between 10 and 90 until 2007, when 128 applications were filed. Year 2008 was quieter with only 58 new applications, but in 2009, 150 applications were filed towards gold exploration and 144 of these were submitted by Agnico-Eagle Finland Oy for exploring the area around the Suurikuusikko deposit.

The exploration budgets in gold and nickel exploration in Finland were available from 1999 onwards. In Figs. 10A and 10B, they are divided into three groups based on the exploration stage (grassroots, late stage & feasibility, mine site) and the size of the exploration company (junior, intermediate, major), respectively. For gold, the budgets show a noticeable change in the amount of investment from 3.2 €M in 1999 to 31.6€M in 2011 and 2012. The distribution of investment by stages has also experienced a change from grassroots- and late stage & feasibility-oriented to mine site exploration,
with the large investment in the mine site exploration being due to opening of new gold mines in Finland. A similar trend can be seen in the lower graph, where the focus of investment in exploration changes from junior and intermediate companies to major companies around 2010. For nickel, the exploration budget was 1.6 €M in 1999 and reached its peak, 30.1 €M, in 2012.

**FIGURE 10.** Budgets in gold and nickel exploration in Finland in 1999-2015 based on the exploration stage (A) and the company size (B). Data source: SNL Metals & Mining, 2016.
The gold prices (Fig. 11) showed nearly constant growth since 1998 (245 €/oz) until 2012, when it reached its highest annual average value of 1260 €/oz. In 2013, the gold price dropped to 876 €/oz, but regained some of its previous value during the two following years. For nickel, the price changes have been more dramatic during the past two decades, ranging from 3 445 €/t in 1998 to 25 802 €/t in 2006.

![Yearly average prices of gold and nickel 1995-2015](image)


The yearly exploration budgets and metal price averages were plotted on scatter charts with the total area claimed for gold or nickel exploration each year to test the dependencies between these variables and to see, whether a change in metal prices or exploration budgets is a good indicator/predictor of changes in the extent of exploration. For the relationship between the gold price and exploration area, the scatter charts (Figs. 12A & B) give an $R^2$ value of 0.75, whereas the $R^2$ value for exploration budget versus exploration area is 0.45. This could be interpreted that in Fig. 12A, 75% of the dependent variable (area) show correlation with the independent variable (gold price) and 75% of the changes in the area claimed for gold exploration could possibly be explained by gold prices. In the case of the budgets for gold exploration in Finland, the number is 45%. Perhaps this number is lower because the annual investment in gold exploration in Finland was not exclusively focused on the study area.
FIGURE 12. Scatter charts showing the relationships between A) the gold price and the area claimed for gold exploration and B) the exploration budget and the area claimed for gold exploration. Data sources: Tukes, SNL Metals & Mining.

Next, the p values for these diagrams were calculated by using the regression analysis tool in Excel. The p values indicate whether the independent variables are good predictors of changes in dependent variables or not and should be <0.05 if the independent variable is a reliable predictor of change. For the gold price-area comparison, p value is 0 and for the exploration budget, p value is 0.003. This suggests that both of the variables, gold price and exploration budget, can be used to predict changes in the extent of the exploration and land area claimed for it in the study area.

The area claimed for nickel exploration and its relationship with the nickel price and exploration budget is a more complicated issue, perhaps due to the fact that compared to gold, there is more unevenness in all of the plotted variables. Figures 13A and 13B show scatter graphs for nickel. The $R^2$ value for the relationship between area and nickel price is 0.003 and for area and exploration budget 0.028, meaning that only tiny fraction of change in the area claimed for nickel exploration could possibly be explained by nickel prices and amount of investment. The calculated p values are 0.803 and 0.519, respectively, which are significantly above the cut-off value of 0.05. This could mean that the nickel price and investment in nickel exploration in Finland are not reliable.
factors in predicting or explaining the changes in the extent of nickel exploration in the study area.

FIGURE 13. Scatter charts showing the relationships between A) the nickel price and the area claimed for nickel exploration and B) the exploration budget and the area claimed for nickel exploration. Data sources: Tukes, SNL Metals & Mining.

As mentioned earlier, the changes in price for nickel have been more dramatic than for gold and also, the number of active nickel exploration permits and area claimed for it increased drastically in 2014 when the majority of granted exploration permits, 472 out of 544, were granted towards nickel exploration in the study area. This creates two overlying points in the scatter charts (Fig. 13A & B) which deviate significantly from the others. These points represent years 2014 and 2015. When these two are removed, the $R^2$ value for the relationship between area and nickel price is 0.3303 and for the relationship between area and investment 0.1611. These numbers mean that 33% of change in the size of the total exploration area for nickel could be explained by nickel prices and 16 % could be explained by the amount of investment towards nickel exploration. The regression analysis gives p values of 0.0101 and 0.1381, respectively, meaning that nickel price could be used to predict changes in the extent of the exploration area, whereas the p value for the relationship between exploration budget
and total exploration area for nickel still exceeds the cut-off value of 0.05 and therefore cannot be used as a reliable predictor.

For the VMS Cu-Zn ore type, no time series or scatter charts could be constructed because there were only three exploration permits of this type granted for the study area. Zinc exploration budgets in Finland have been low compared to other commodities and have primarily focused on grassroots exploration. Budget-wise, the peak years in zinc exploration were 2000 and 2001, when 2.5 €M and 3.6 €M, respectively, were invested in grassroots exploration by major companies. Since then, the annual investment in zinc has been nearly non-existent, remaining between 0.1 and 1.1 €M, and made almost exclusively by junior and intermediate companies. The budget trends for copper, on the other hand, have experienced a considerable increase in recent years. From 2000 to 2003, the budgets remained below 1 €M, but then started to grow almost on a yearly basis, reaching 14.7 €M in 2015. The three VMS Cu-Zn exploration permits in the study area were granted in 2001, which coincides with the investment peak in zinc exploration budgets. In general, it is clear that a drastic decline in investment towards exploration in Finland has occurred for the past 3 to 4 years (2012-2015) and not many new applications have been filed towards orogenic gold, magmatic nickel-copper and VMS zinc-copper exploration in the study area.

However, according to a review on mining industry in Finland by Ministry of Economic Affairs and Employment (TEM) in November 2016, the dawning trend of the rise in base metal prices gives hope for the future of mining industry in Finland. The price of gold was steadily rising in 2016, scattering between 1032 and 1206 €/oz in monthly averages (SNL Metals & Mining). The global demand for zinc is estimated to surpass the current zinc supply and the copper market is estimated to stay approximately the same. The nickel markets, on the other hand, are difficult to predict and are affected by notable economic and political uncertainties around the globe (TEM 2016). The activation of exploration operations in Finland can already be seen as the permitting authority Tukes is experiencing a rise in the number of new exploration permit applications and is hiring new personnel to handle these new permits (Liikamaa/Tukes 2017). Also, information in mining and exploration company media releases (http://new.gtk.fi/informationservices/explorationnews/index.html) is showing signs of re-activation and is up-to-date with recent exploration news.
6.2 Mining

The mining history of the study area dates back to 19th century, when the historic Juvakaisenmaa mine was opened, operating for four years in 1840-1843 (Puustinen 2003). The mine utilized an IOCG deposit and produced primarily iron. Two other mines of the IOCG type have also been exploited in the area, Rautuvaara in 1962-1988 and Hannukainen in 1978-1990 shown in Fig 1, but the ore produced by these mines is not included in the calculations presented in this chapter.

The mines related to magmatic Ni-Cu, orogenic gold and VMS deposits and their production numbers from 1953 to 2015 are summarized in Table 3. The oldest mine that belongs to the selected ore types is the Sirkka mine, which was established in 1953. It was short-lived and only remained in operation for three years, producing 9500 tonnes of ore. After its closure, it took nearly two decades for the next mine to be opened. The Pahtavuoma mine was in operation only for one year in the 1970s and again in the 1990s (Puustinen 2003).

![Figure 14](image-url)

TABLE 3. Operating and closed mines of the study area from 1953 to 2015 and their ore and wall-rock tonnages, production by commodity and production in total. This table only contains the production volumes of deposits which are genetically of magmatic Cu-Ni, orogenic Au or VMS type and, for example, the IOCG mines in the Kolari area are not included. Sources: Puustinen (2003), FODD (Eilu et al. 2016), SNL Metals & Mining, Tukes and GTK.

<table>
<thead>
<tr>
<th>MINE</th>
<th>Excavated</th>
<th>Ore mined</th>
<th>Waste rock</th>
<th>Commodity production</th>
<th>Total production</th>
<th>When mined</th>
<th>Genetic type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tonnes</td>
<td>tonnes</td>
<td>tonnes</td>
<td>Ni (t)</td>
<td>Cu (t)</td>
<td>Pt (kg)</td>
<td>Au (kg)</td>
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<td>1331</td>
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<td>Kutuvuoma</td>
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<td>17 080</td>
<td></td>
<td>30</td>
<td></td>
<td></td>
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<td>Pahtavaara</td>
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<td>8 952 440</td>
<td></td>
<td>10 855</td>
<td></td>
<td></td>
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<td>Pahtavuoma</td>
<td>629 209</td>
<td>295 239</td>
<td>333 970</td>
<td></td>
<td>3 157</td>
<td>5 310</td>
<td>3 162</td>
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<td>5 574 205</td>
<td>1 992 608</td>
<td>3 581 597</td>
<td></td>
<td>5 210</td>
<td>6 467</td>
<td>5 657</td>
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<td>Sirkka</td>
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<td>9 500</td>
<td>5 500</td>
<td>85</td>
<td>48</td>
<td>8</td>
<td>15</td>
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<td>Suurikuusikko</td>
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<td>8 203 321</td>
<td>37 128 062</td>
<td></td>
<td>29 735</td>
<td>747</td>
<td>30.48</td>
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<td>Total</td>
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<td>39 184 745</td>
<td>122 285 999</td>
<td></td>
<td>31 161</td>
<td>66 023</td>
<td>3 428</td>
</tr>
</tbody>
</table>

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From the 1950s until 1989, mining had only taken place during six years and the total amount of ore mined annually did not exceed 20,000 tonnes. The opening of the Saattopora mine in 1988 and the Pahtavaara mine in 1996 increased the mining volumes and on average, the amount of mined ore reached approximately 300,000 tonnes annually until the Suurikuusikko mine began operation in 2009 and the production volumes soared. Kutuvuoma was a test mining project undertaken by Terra Mining Oy in 1999 (Tukes), which seems to not have led to any further operations at that time. The opening of the Kevitsa mine in 2012 pushed the volume of mined ore even higher, resulting in a record high of 6.9 Mt in 2014 (Fig. 14). In Fig. 14, the years prior to 1988 were chosen to be left out due to the fact that the mining volumes were considerably lower compared to recent years and would not show in the diagram. After the closure of the Saattopora mine in 1995 and the Pahtavaara mine in 2014, there are only two mines currently in operation in the study area.

Between 1953 and 2015, the mines in the study area have produced 98,122 tonnes of metals in total. Of these, the vast majority, 98,060 tonnes, were produced from base metals, of which 67.8% consisted of copper, 31.8% of nickel and 0.4% of cobalt. The production of precious metals in this time period totals to 61,125 kg, of which 80% consisted of gold, 9.9% of silver, 5.6% of platinum, and 4.5% of palladium. More constant metal production began with the opening of the Saattopora mine in 1988 and Fig. 15 represents the annual production of base and precious metals in the study area during 1988-2015. In 2012, Finland became the leading producer of platinum group metals (PGM) in the EU owing to the Kevitsa mine (Pokki 2016), and currently, the Suurikuusikko deposit is the largest gold producer in Europe (Wyche et al. 2015). The Suurikuusikko and Kevitsa mines also have the largest positive effect on employment and general livelihoods in their municipalities compared to other Finnish mining towns (Laukkonen & Törmä 2014).

The latest mine in the study area, Kevitsa, as mentioned before, was opened in 2012 and since then, the volumes of total excavation have been rising every year (Fig. 14).

According to the report on the development of the Finnish mining industry and its challenges in 2010-2020, published by the Ruraiia Institute (Laukkonen & Törmä 2014), the Kevitsa mine got a renewed environmental permit in 2014, which allows the maximum annual ore production of 10 Mt. In 2014 and 2015, the ore production at
Kevitsa was 6.6 Mt and 6.9 Mt, respectively, which means that there is still plenty of room for increasing excavation volumes in the following years. In total, 22.8 Mt of ore has been mined at Kevitsa (Table 3), and it is estimated that the mine has still about 224 Mt of resources left (Eilu et al. 2016). Based on these data, the mining operation at Kevitsa could easily continue for the next twenty years. In June 2016, Kevitsa was sold by the Canadian First Quantum Minerals to a Swedish company, Boliden.


For the Suurikuusikko mine, the estimated annual gold production in 2014 was 4665 kg (Laukkonen & Törmä 2014) and later it has been raised to 6000 kg (Agnico Eagle 2016). Based on the current knowledge on the ore reserves at Suurikuusikko, the mine is estimated to operate until 2036, and its operation may continue even further depending on the results of on-going exploration (Agnico Eagle 2016).

The mining industry has already grown noticeably in Finland as a whole, but also in the study area (Figs. 14 & 15). If the economic and political circumstances stay favorable, this growth is expected to continue in the future (Tuusjärvi et al. 2014).
7 GIS ANALYSIS OF MINERAL POTENTIAL AND EXPLORED AREAS

7.1 METALS ALREADY FOUND

In the Fennoscandian Ore Deposit Database (FODD), there are a total of 19 known mineral deposits of interest in the study area: 14 orogenic gold, 4 magmatic Ni-Cu and 1 VMS Cu-Zn deposit. In Fig. 16, the metals already found in the study area are shown in a raster intensity map, where the tonnage value is the combined number of reserves, resources, and already mined ore. Several of the known deposits are very small in size and are estimated to have less than 1 Mt of ore. These are marked with one color (pink), but deposits with a total tonnage more than 1 Mt are all represented with their own color code on the map. Only two deposits, Kevitsa being the largest and Suurikuusikko second largest, are considered large deposits in this study.

FIGURE 16. Raster intensity map of orogenic Au, magmatic Ni-Cu and VMS deposits and the total tonnage of metals already found in the study area. Exploration tenements active between 1995 and 2015 are shown in the background. Total tonnage = reserves + resources + already mined ore. Data source: Fennoscandian Ore Deposit Database (Eilu et al. 2016), Valtaustietokanta / Mining Registry (Tukes) as April 1, 2016.
The Sakatti Cu-Ni-PGE deposit is shown as white with a black border, and at the time of making this GIS analysis, it had only been evaluated to be a potentially large deposit without any accurate estimates. In March, 2017 Anglo American published an inferred resource estimate of 40.9 Mt for Sakatti, which would make it the third largest deposit on the study area.

The total tonnage values obtained from the FODD were given to exploration tenement or mining permit polygons with the same name (or known alternative name) as the known deposits in ArcGIS. Then these polygons were transformed into a raster form in order to make the cell size bigger and the sizes of the deposits more realistic on the map. A more detailed description on the construction of Fig. 16 is given in Chapter 4 of this thesis.

Active gold exploration in the study area started after the discovery of the Saattopora deposit in 1985, and the majority of the gold discoveries were made during the time period between the late 1980s to middle 1990s (Niiranen 2015). Even though the number of exploration permits and number of companies undertaking exploration work in the study area has increased over the past 20 years, only two new deposits have been discovered since 1995, Lomalampi in 2004 and Sakatti in 2009 (Table 4.)
**TABLE 4.** Orogenic gold, magmatic nickel and VMS deposits of the study area sorted by discovery year. Sources: FODD (Eilu et al. 2016), Mineral Deposits and Exploration (GTK 2017).

<table>
<thead>
<tr>
<th>Name</th>
<th>Discovery year</th>
<th>Size</th>
<th>Total tonnage, Mt</th>
<th>Genetic type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sirkka</td>
<td>1939</td>
<td>Small</td>
<td>0,25</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Kelujoki</td>
<td>1939</td>
<td>Small</td>
<td>1,50</td>
<td>Magmatic Ni</td>
</tr>
<tr>
<td>Riihkonkoski</td>
<td>1969</td>
<td>Small</td>
<td>9,45</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Pahtavuoma Zn</td>
<td>1971</td>
<td>Medium</td>
<td>21,40</td>
<td>VMS</td>
</tr>
<tr>
<td>Saattopora Cu</td>
<td>1972</td>
<td>Medium</td>
<td>11,60</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Kettukkuusikko</td>
<td>1977</td>
<td>Small</td>
<td>0,44</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Tepsa</td>
<td>1982</td>
<td>Showing</td>
<td>0,20</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Pahtavaara Au</td>
<td>1985</td>
<td>Small</td>
<td>8,08</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Saattopora Au</td>
<td>1985</td>
<td>Small</td>
<td>2,16</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Suurkuusikko</td>
<td>1986</td>
<td>Large</td>
<td>63,45</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Hirvilavanmaa</td>
<td>1987</td>
<td>Small</td>
<td>0,11</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Kaaresselkä</td>
<td>1987</td>
<td>Small</td>
<td>0,30</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Kuohto</td>
<td>1987</td>
<td>Small</td>
<td>1,82</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Kevitsa</td>
<td>1987</td>
<td>Large</td>
<td>246,93</td>
<td>Magmatic Ni</td>
</tr>
<tr>
<td>Soretialehto</td>
<td>1989</td>
<td>Showing</td>
<td>0,01</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Kutuvuoma</td>
<td>1993</td>
<td>Small</td>
<td>0,07</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Levijärvi-Loukinen</td>
<td>1994</td>
<td>Small</td>
<td>2,57</td>
<td>Orogenic gold</td>
</tr>
<tr>
<td>Lomalampi</td>
<td>2004</td>
<td>Small</td>
<td>3,06</td>
<td>Magmatic Ni</td>
</tr>
<tr>
<td>Sakatti</td>
<td>2009</td>
<td>Potentially large</td>
<td>NA</td>
<td>Magmatic Ni</td>
</tr>
</tbody>
</table>
7.2 Spatial Comparison of Known Deposits and Mineral Potential

In order to compare the already known deposits with mineral potential and prospectivity in the study area spatially, the raster intensity map of orogenic Au, magmatic Ni-Cu and VMS Cu-Zn deposits, which was presented in the previous chapter (Fig. 16), was laid on top of pre-existing prospectivity maps (Nykänen et al. 2011, 2014, V. Nykänen, pers. comm. 2016) in ArcGIS. This type of maps covering the study area have been compiled for nickel, orogenic Au and VMS, and the prospectivity maps for each deposit type have furthermore been divided into four different layers based on their mineral potential level. The layers represent a low, moderate, high and very high potential, of which the two latter ones are of most interest. The spatial modelling techniques used in ArcGIS to construct these maps are briefly described in Chapter 4. In Figs. 17A-D, each map depicts one of these prospectivity levels and the prospectivity for each ore type is depicted with different color.

The areas of very high mineral potential are very small and confined to a handful of places in the study area, especially in the case of nickel. One of the very high nickel potential spots on the map falls within the boundaries of the Kevitsa deposit, but the rest are outside of any known deposits. For orogenic gold, the areas of very high potential seem to broadly follow the Sirkka thrust zone, which is logical considering the favourable environments for orogenic gold deposition, but no known gold deposits are located in these specific areas of very high gold potential. When looking at the map of high mineral potential (Fig. 17B), nearly all of the already known deposits fall within the prospective areas for nickel and gold. For the VMS type, the areas of both very high and high potential are noticeably larger than for the two above mentioned ore types, and based on these prospectivity maps, all of the known deposits fall within either of these areas. Also, the exploration tenements are visible in the background of these figures, and based on this map display, they seem to broadly be located in the areas of high mineral prospectivity.
Figure 17. Comparison of the known deposits and mineral potential of orogenic gold, nickel, and VMS. 
IA) Areas of very high mineral potential and B) areas of high potential. Colorful polygons represent the 
known deposits and are explained in Fig. 16. Data sources: Nykänen et al. 2011, 2014, V. Nykänen, pers. 
Figure 17. Continued. Comparison of the known deposits and mineral potential of orogenic gold, nickel and VMS. C) Areas of moderate mineral potential and D) areas of low potential. Colorful polygons represent the known deposits and are explained in Fig. 16. Data sources: Nykänen et al. 2011, 2014, V. Nykänen, pers. comm. 2016, Fennoscandian Ore Deposit Database (Eilu et al. 2016).
8 Discussion

The Finnish mineral resources and production numbers are low when compared to the largest producer countries of precious and non-ferrous metals globally. Nevertheless, Finland has been ranked by the Fraser Institute to be among the top ten most attractive countries for exploration investment for the past five consecutive years and currently, it seems that investments are increasing. The number of new exploration permit applications is on the rise as well (Liikamaa 2017). When concentrating solely on Europe, Finland is a very important mineral resource producer. The study area is a host for the largest gold producer, Suurikuusikki, in Europe and is also the leading producer of platinum group metals (PGM) in the EU owing to the Kevitsa mine. These two mining projects have been successful, and the production volumes are even expected to rise in the coming years. Based on the excellent geoscientific base data in Finland, expert opinions and computer models, there is still potential for new discoveries as many commodities remain highly underexplored (GTK 2017).

Historically, of the three ore types discussed in this thesis, the exploration in the study area has been mostly concentrated on gold and most of the known deposits (Table 4) represent orogenic gold occurrences. The CLGB is the main gold-mineralized area of the Paleoproterozoic Karelian domain, with 40 drilling-indicated deposits and occurrences. These deposits and occurrences represent the standard gold-only type, but the anomalous metal association subtype is also common in the Karelian domain of Finnish bedrock (Eilu et al. 2015). The mineral potential maps (Fig.17) of the study area clearly suggest that the VMS type has the most extensive areas of very high and high mineral potential, yet not many deposits have been discovered. By looking at the time series of mineral exploration compiled in this work, it seems that not much effort has been put towards exploration of new VMS deposits in the study area, but perhaps there are more complicated reasons as to why there is only one known VMS deposit and 3 exploration permits active towards VMS exploration between 1995 and 2015. Eilu (2015) recognized that almost all of the CLGB gold occurrences can be placed into the orogenic gold category, even when they exhibit an anomalous metal association of typically Cu±Co±Ni. There also exist a few base metal-rich (Cu ± Zn, Ag, Pb) syngenetic VMS occurrences in the CLGB that appear to be overprinted by orogenic gold (e.g., Riikokkoski). The complicated deformation history of the study area and this
possible overprinting make it difficult to classify all deposits with 100% certainty without radiometric dating of mineralization processes (Eilu 2015). For example, the genetic type of Pahtavaara deposit in the study area is still unclear (Eilu et al. 2015) and in the FODD (Eilu et al. 2016), the Tepsa and Riikonkoski deposits have no genetic type and Saattopora Cu is marked as a polygenetic deposit. For the purpose of this thesis, these deposits of an unclear genetic type were placed in the orogenic gold category, but one can only speculate whether the confusion and obscurity about the genetic type of the ore deposits contributes to the scarcity of VMS discoveries in the study area.

The GTK has published quantitative assessments of undiscovered resources for multiple commodities and ore types, including orogenic gold deposits, VMS deposits and Ni-Cu deposits (Rasilainen et al. 2012, 2014, Eilu et al. 2015), in which the undiscovered resources have been estimated down to the depth of one kilometer using a three-part quantitative assessment method. In these assessments, the Finnish bedrock is divided into permissive tracts, which are defined as follows: a permissive tract is an area in which the geology permits the existence of mineral deposits of the type under consideration. It is, however, important to distinguish between areas favorable for the existence of deposits and permissive tracts: the former are a subset of the latter. For each tract, an expected number (mean estimate) of undiscovered deposits is calculated alongside a median estimate of undiscovered ore in tonnes. According to the assessments, the study area potentially still, on average, contains 20.2 new orogenic gold deposits with 207 tonnes of gold and 100 Mt of ore in three permissive tracts: Kittilä Group, Sattanen-Kolari and Vuojaari Group. The adjacent Kittilä Group and Sattanen-Kolari tracts are estimated to contain 46% of the undiscovered gold in the Karelian domain in Finland (Eilu et al. 2015). For magmatic nickel and copper, the undiscovered resources were estimated for intrusive and komatiitic type deposits. Undiscovered deposits and ore tonnages for potential new Kevitsa-type deposits have not been estimated. The four permissive magmatic Ni-Cu tracts in the study area occupy 967 km² of land, are estimated to contain 5.9 new deposits with median undiscovered 9.64 Mt of ore and 40620 t of nickel, 9260 t of copper and 1466 t of cobalt. The tracts taken into account here are Jalokoski and Moskuvaara representing the intrusive type, and Nilivaara and Sattasvaara being of the komatiitic type (Rasilainen et al. 2012). For VMS-type, there are also four permissive tracts in the study area occupying 3979 km² of
land area with an estimate of 7.3 undiscovered deposits with 20 Mt of ore and 251 000 t nickel and 146 000 t zinc. These tracts are called Pahtavuoma, Sattasvaara, Vesmajärvi, and Pulju (Rasilainen et al. 2014). The median undiscovered VMS metal tonnages are much higher than for the other types, perhaps reflecting the contrast between the very high VMS mineral potential and the low number of known deposits on the study area.

When compared to the amount of ore already found in the area (Table 4), the numbers can perhaps be put into more perspective. The amount of known orogenic gold ore is 100.52 Mt, which is nearly exactly the same amount as the median estimation of undiscovered ore in orogenic deposits. Also, the amount of estimated undiscovered VMS ore is close to that of already found 21.4 Mt of ore at Pahtavaara. Because Kevitsa is such a large deposit, the number of already found magmatic Ni-Cu type ore, 251.7 Mt, greatly exceeds the estimates of undiscovered ore. If Kevitsa is not taken into comparison, since there are no estimates of the number of undiscovered deposits of the Kevitsa type, the amount of already found magmatic Ni-Cu ore is 4.56 Mt. In this case, the amount of undiscovered magmatic Ni-Cu ore in the study area is roughly twice the amount of already found ore.

Despite the fact that the quantitative assessments indicating that the study area could still contain 33.4 undiscovered deposits and even though the number of exploration permits and number of companies undertaking exploration work in the study area has increased over the past two decades, only two new deposits have been discovered since 1995. This sparks questions whether exploration has been conducted in right places? In Figs. 17A-D, the exploration tenements are visible in the background and based on this map display, they seem to be located broadly in the areas of high mineral prospectivity.

Furthermore, the amount of investment towards exploration in Finland increased significantly from 1999 until 2012, yet the number of new discoveries remained low. The trends and distribution of exploration budgets (Fig. 10A) show a noticeable investment change from grassroots exploration to late stage & feasibility study and mine site-oriented exploration. This is probably due to opening of new mines and the exploration of continuations for already known deposits near the mines. For example, the depth of Suurikuusikko deposit is still open and under exploration (Agnico Eagle, 2017). After 2012, the amount of investments dropped and the scarcity of new deposit discoveries have been thought to be a symptom of the downhill experienced by the
exploration and mining industry as a whole in the recent years. The lack of new discoveries and the lessening of mineral resources are expected to change the strategies of mineral exploration in the future (TEM 2016). Investments are returning and drilling activities seem to have already taken a turn for better in Finland as the amount of exploration drilling rose from 130 km in 2015 to 178 km in 2016. This is an increase of 37% despite the fact that investment towards exploration is still in decline globally (Liikamaa/Tukes, 2017). Also junior exploration companies operating in Finland are starting to gain more investments (TEM, 2016), which could indicate more grassroots exploration in the future.
9 CONCLUSIONS

Based on the available data and compiled time series, it is clear that orogenic gold is the most sought-after commodity in the study area. In terms of the number of exploration tenements, magmatic Ni-Cu comes as a close second, but not nearly as many deposits of this type have been discovered. Out of 1938 exploration tenements granted between 1995 and 2015, time series were compiled for orogenic gold and magmatic Ni-Cu. For VMS exploration, there the number of tenements was too low to compile a time series or to test relationships with independent variables. The calculations for coefficient of determination and regression analysis indicate that metal price and exploration budget are reliable variables and can be used to predict change in the area claimed for orogenic gold exploration. For magmatic Ni-Cu, the situation was more complicated and exploration budget did not reach the status of a reliable predictor. On the other hand, nickel price, with some caution, may be used in predicting a change in the size of the exploration area claimed for magmatic Ni-Cu exploration.

The statistical dataset coupled with time series of exploration tenements shows that the exploration boom in the study area has been ongoing since 2003, when the number of active exploration permits hit 200 and has not gone below this number since. The exploration towards VMS in the study area has been minimal, even though there are large areas of very high and high mineral potential for VMS deposits. Based on the spatial comparison, the already known deposits are all located mainly in areas of high mineral potential and it seems that most mineral exploration has also been carried out in these high-prospectivity areas. Nevertheless, out of the 19 known deposits, only two have been discovered after 1995. Yet, quantitative assessments on undiscovered deposits indicate that more than 30 deposits could still be undiscovered on the study area.

There are currently two mines, Suurikuusikko and Kevitsa, in operation and mining volumes have been rising every year since 2012. Both mines have permits allowing them to increase their annual ore production and operations are expected to last possibly for more than 20 years. Also, the future for mineral exploration is looking brighter as the investments and drilling activities have recently shown signs of recovery in Finland.
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REFERENCES


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