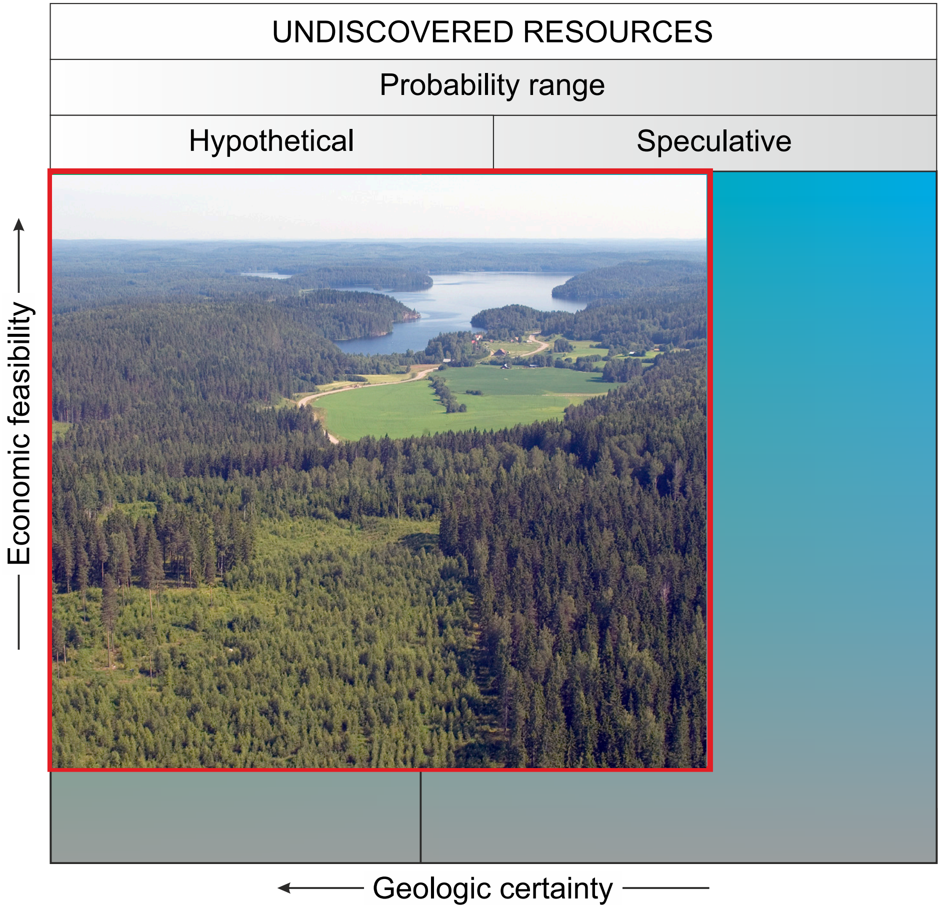

GTK

Assessment of undiscovered PGE, Ni, Cu, Zn, and Au resources in Finland

Kalevi Rasilainen and Pasi Eilu

Front cover photo: Jari Väätäinen, GTK
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Introduction

Throughout the history, the demand for mineral resources has increased with the continuing growth of the world population and the rise in the average material standard of living. In tandem with this trend, exploration for and the development of new mineral resources all over the world are facing increasing competition from other land uses (e.g., Briskey & Sculz 2007, Rasmussen 2011). Recycling can cover a significant part of the demand of a commodity, as is the case for gold and platinum. However, recycling cannot cover all the growing demand of any particular metal, not even for commodities of which only very little is lost during production and manufacturing, such as gold (e.g., Wellmer & Dalheimer 2012).

In the modern world, a country, or even the European Union, can no longer rely on the availability of imported raw materials for its manufacturing and other industries (European Commission 2014). We need to know our mineral resources and how they might be expanded. The essential information includes the location of the known resources, the location and amount of the possibly existing, yet undiscovered resources, and the uncertainty related to their existence.

In this handout, we provide information concerning known and undiscovered mineral resources in Finland. We summarise the assessments of several important metals in Finnish bedrock, carried out by the Geological Survey of Finland during 2008–2014.

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GTK assessment of undiscovered mineral resources

Geological Survey of Finland (GTK) has carried out assessments of undiscovered mineral resources since 2008. The assessment process follows the three-part quantitative method, and the results achieved by the end of 2014 have been reported in full detail by Rasilainen et al. (2010, 2012, 2014) and Eilu et al. (2015). Here, we summarise the method used and the main results achieved for platinum (Pt), palladium (Pd), nickel (Ni), copper (Cu), zinc (Zn), and gold (Au). The undiscovered resources of these metals were assessed down to the depth of one kilometre for eight deposit types (Table 1), some of which contain significant by-product cobalt (Co), molybdenum (Mo), lead (Pb), or silver (Ag), and these by-product resources were also estimated.

The mineral deposit types selected for the assessment (Table 1) are among those regarded the most important for containing significant undiscovered metal resources in Finland. Another reason for selecting these deposit types is that they are well-constrained and enough reliable information from well-known deposits is available for the construction of the necessary deposit models. For the metals listed above, certain important deposits in Finland and certain deposit types that we believe to occur in Finland are not included in this assessment. This is dominantly because not enough grade and tonnage data exist for them to construct a grade-tonnage model necessary for the assessment (e.g., for Kevitsa and Talvivaara types of Ni deposits). Other reasons for exclusion include too high uncertainty in a deposit model (i.e., not enough is known even globally for the deposit type) and the lack of evidence into which genetic type a deposit belongs to. The deposit types hosting the metals listed above, but not included in the assessments are listed in Table 2.

The GTK assessment work is continuing and in 2015 the undiscovered chromium resources in Finland will be estimated. During 2016-2019, the assessment will cover titanium, vanadium, phosphorus, lithium and the REE.

Table 1. Deposit types and metals fully assessed for undiscovered mineral resources in Finland. Abbreviations used in this paper are given in a separate column. The reference gives the report where the results of the assessment are described in detail.

Deposit type	Abbreviation used	Commodities	Reference
Mafic-ultramafic layered intrusion-hosted reef-type nickel-copper-platinum group element	Reef-type PGE	Pt, Pd, Au, Ni, Cu	Rasilainen et al. (2010)
Mafic-ultramafic layered intrusion-hosted contact-type nickel-copper-platinum group element	Contact-type PGE	Pt, Pd, Au, Ni, Cu	Rasilainen et al. (2010)
Synorogenic mafic-ultramafic intrusion-hosted nickel-copper	Intrusive Ni-Cu	Ni, Cu, Co	Rasilainen et al. (2012)
Komatiite-hosted nickel-copper	Komatiitic Ni-Cu	Ni, Cu, Co	Rasilainen et al. (2012)
Volcanogenic massive sulphide	VMS	Cu, Zn, Pb, Ag, Au	Rasilainen et al. (2014)
Outokumpu-type copper-zinc-cobalt	Outokumpu-type	Cu, Zn, Co, Ni	Rasilainen et al. (2014)
Porphyry copper	Porphyry Cu	Cu, Mo, Ag, Au	Rasilainen et al. (2014)
Orogenic gold	Orogenic Au	Au	Eilu et al. (2015)

Table 2. Deposit types that were not included or were only partly included in the assessments although they are known or believed to occur in Finland.

Deposit type	Reason for exclusion	Additional notes
Talvivaara Ni-Zn-Cu-Co	Not enough grade-tonnage data.	Permissive tracts were delineated but undiscovered metal tonnages were not estimated.
Kevitsa Ni-Cu-PGE	Not enough grade-tonnage data.	
Sakatti	Not enough information.	
Pahtavaara Cu-Au	Uncertain deposit type, no analogies in Finland.	
Haveri Cu-Au	Uncertain deposit type, no analogies in Finland.	
Granitoid-related Au	Uncommon or nonexistent in Finland.	
Palaeoplacer Au	Insignificant in Finland, insufficient grade-tonnage data.	
Placer Au	Unimportant in Finland, insufficient grade-tonnage data.	
Epithermal Au	Not enough consistent Precambrian grade-tonnage data.	Permissive tracts were delineated but undiscovered metal tonnages were not estimated.
Iron oxide-copper-gold	Mostly Fe deposits where Cu and Au typically form a small part of the in-situ value of the deposit.	
Sediment-hosted stratiform Cu	No obvious examples known in Finland. Probability of existence and importance for Cu endowment in Finland considered small.	Indirect indications for existence in the Peräpohja and Kuusamo belts.
Subaerial volcanic-hosted (red bed) Cu	No obvious examples known in Finland. Probability of existence and importance for Cu endowment in Finland considered small.	Indirect indications for existence in the Peräpohja and Kuusamo belts.
Dolerite-hosted Ni	Of minor importance in Finland, insufficient grade-tonnage data.	
Soapstone deposits (Ni)	Only minor Ni potential in FInland, insufficient grade-tonnage data.	
Lateritic Ni in northern Finland	Insignificant in Finland, insufficient grade-tonnage data.	

Assessment method

The procedure selected for the GTK assessments is based on the three-part quantitative assessment method developed by the U.S. Geological Survey (USGS) starting from the mid-1970s (Singer 1993, Singer & Menzie 2010). It must be emphasised that the method does not provide mineral resource or reserve estimates concordant with the present industrial standards such as the JORC, CRIRSCO, NI 43-101, PERC, and UNFC codes. The results of undiscovered resource assessments should never be confused with proper reserve or resource estimates based on these international standards. Rather, the assessment process produces probabilistic estimates of the total amount of metals in situ in undiscovered deposits. The modification of the process used in the GTK assessments does not take into account the economic, technical, social, or environmental factors that affect the potential for economic utilisation of a resource. Hence, part of the estimated undiscovered resources are located in subeconomic occurrences (Fig. 1, Table 3), and it might be more appropriate to use the term 'metal endowment', which is not directly dependent on economic or technological factors.

The assessments are performed by deposit type (genetic type). The three parts of the method are: (1) evaluation and selection or construction of a descriptive model and a grade-tonnage model for the deposit type, (2) delineation of areas permitted by the geology for the deposit type (permissive tracts), and (3) estimation of the number of undiscovered deposits of the deposit type within the permissive tracts. Finally, the estimated number of deposits is combined with the grade and tonnage distributions from the deposit model to assess the total undiscovered metal endowment.

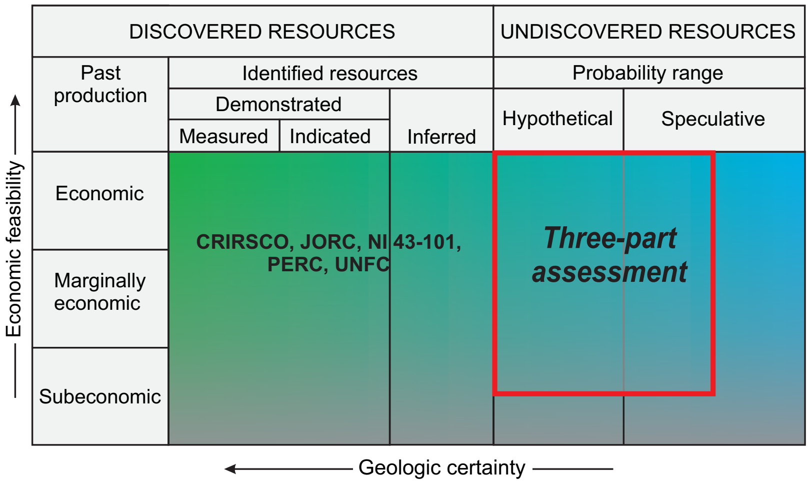

Figure 1. *Classification of mineral resources used in GTK assessments (modified from USGS NMRA Team 2000). Economic feasibility increases upwards and geological certainty increases to the left.*

Table 3. Some terms essential to the proper understanding of this report. These follow the usage by the minerals industry and the resource assessment community (e.g., USGS NMRA Team 2000, Committee for Mineral Reserves International Reporting Standards 2013).

Category	Definition
Well-known mineral deposit	A completely delineated mineral deposit, for which the identified resources and past production are known
Undiscovered mineral deposit	A mineral deposit believed to exist less than 1 km below the surface of the ground, or an incompletely explored mineral occurrence within that depth range that could have sufficient size and grade to be classified as a deposit
Well-known resources	Identified resources that occur in completely delineated deposits included in grade-tonnage models
Discovered resources	The total amount of identified resources and cumulative past production
Undiscovered resources	Resources in undiscovered mineral deposits whose existence is postulated based on indirect geological evidence
Hypothetical resources	Undiscovered resources in known types of mineral deposits postulated to exist in favourable geological settings where other well-explored deposits of the same types are known
Speculative resources	Undiscovered resources that may occur either in known types of deposits in favourable geological settings where mineral discoveries have not been made, or in types of deposits as yet unrecognized for their economic potential

The GTK assessment process

An assessment team was formed for each mineral deposit type. The team members were GTK experts familiar with the deposit type and local geology in various parts of Finland. The experts most familiar with the geology of the area in question delineated the initial permissive tracts. The boundaries of the tracts were modified according to comments of the other assessment team members. The permissive volumes of rock were delineated down to the depth of one kilometre.

The number of undiscovered deposits within each permissive tract was estimated in a series of workshops by the members of the assessment teams and other GTK experts. The process follows the Delphi technique (Chorlton et al. 2007), in which each expert makes an estimate independently and all the estimates are then discussed to reach a final consensus estimate. The experts evaluated the number of undiscovered deposits within a permissive tract at 10 %, 50 %, and 90 % confidence levels. If a consensus was not reached in the ensuing discussion, the averages of the estimates at the 90 %, 50 % and 10 % probability levels were used as the final estimates.

The assessment of metal tonnages in the undiscovered deposits was performed separately for each permissive tract using Eminers software (Root et al. 1992, Duval 2012). The software uses the data from the grade-tonnage model and the estimated numbers of undiscovered deposits at the 90 %, 50 % and 10 % probability levels to calculate an average non-parametric frequency distribution for the number of undiscovered deposits within a tract. It fits empirical and log-normal frequency distributions to the ore tonnage and metal grade data in the grade-tonnage model. Finally, the software uses the estimated frequency distributions in Monte Carlo simulation to calculate the probability distributions of ore and metal tonnages in the undiscovered deposits. The estimated empirical ore tonnage and metal grade distributions were used in the simulations of the Finnish undiscovered resources, because they were considered to better represent the grade-tonnage data in cases of deviations from lognormality. Using empirical distributions also helps to avoid the very large estimates of metal tonnages that sometimes might result from using a lognormal model.

Assessment results

Table 4 presents pre-mining metal contents in the Finnish well-known deposits having a significant endowment of the metals assessed. Table 5 summarises the permissive tracts delineated, the estimated numbers of undiscovered deposits and the calculated deposit densities, Table 6 contains the known and estimated undiscovered metal tonnages and Table 7 lists the relative amounts of undiscovered metal endowment for each fully assessed deposit type. Figures 2–4 show the locations of permissive tracts for the deposit types assessed and Figures 5–9 indicate the distribution of the estimated undiscovered resources between the permissive tracts.

Table 4. Discovered resources (see Table 2) in deposit types containing PGE, Ni, Cu, Zn, or Au as a major commodity in Finland. Values in metric tons of metal.

Type	Pd	Pt	Au	Ag	Ni	Co	Cu	Zn	Pb	Fe	No. of deposits
Included in the GTK assessment											
Contact-type PGE	206	52	26	-	223,123	-	430,303	-	-	-	6
Komatiitic Ni-Cu[1]	3.1	2.1	0.2	-	42,003	1,698	7,831	-	-	-	6
Intrusive Ni-Cu[2]	2.6	2.1	-	-	428,709	20,314	187,495	-	-	-	34
VMS	-	-	52	2,638	-	-	997,546	3,589,111	255,129	-	20
Outokumpu-type[3]	-	-	31	381	84,525	117,616	1,486,298	536,644	-	-	10
Porphyry Cu	-	-	14	100	-	-	45,000	-	-	-	1
Orogenic gold	-	-	339	-	-	-	-	-	-	-	15
Not included or only partially included in the GTK assessment											
Talvivaara Ni-Zn-Cu-Co	-	-	-	-	4,556,410	411,326	2,668,692	10,350,499	-	-	1
Kevitsa Ni-Cu-PGE	68	55	32	-	816,995	39,620	1,106,714	-	-	-	1
Epithermal gold	-	-	24	-	-	-	-	-	-	-	1
Pahtavaara (VMS?)	-	-	20	-	-	-	-	-	-	-	1
Iron oxide-copper-gold	-	-	18	-	-	-	406,080	-	-	73,094,400	1

No. of deposits: The number of well-known mineral deposits.
'-: No data, insignificant content for the metal.
[1] PGE and Au data only from three deposits, hence Pd, Pt and Au not included in the grade-tonnage model for komatiite-hosted Ni deposits.
[2] PGE data only from two deposits, hence Pd and Pt not included in the grade-tonnage model for synorogenic intrusive Ni deposits.
[3] Au and Ag data only from five deposits, hence Au and Ag not included in the grade-tonnage model for Outokupu-type deposits.
Data sources: Rasilainen et al. (2010, 2012, 2014), Eilu et al. (2015), and references in these.

Table 5. Permissive tracts and number of known and undiscovered deposits for different deposits types in Finland.

	N of permissive tracts	Area of permissive tracts (km^2)				N of known deposits	N of undiscovered deposits	Cv of undiscovered deposits	Average deposit density (N/km^2)
		Minimum	Maximum	Average	Total				
Orogenic Au: Archaean	8	340	7,150	2,970	23,750	5	18.4	74	0.0035
Orogenic Au: Karelian	13	1,000	12,790	4,700	61,050	2	44.5	75	0.0010
Orogenic Au: Svecofennian	11	90	10,260	2,280	25,040	8	27.3	62	0.0038
Epithermal Au	2	1,470	2,840	2,150	4,300	-	-	-	-
Intrusive Ni-Cu	26	3.9	11,700	2,330	60,500	34	65.8	58	0.019
Komatiitic Ni-Cu	30	3.1	790	160	4,880	6	34.4	109	0.030
Talvivaara Ni-Zn-Cu-Co	15	1.1	70	20	310	1	4.9	-	0.023
Porphyry Cu	10	600	11,160	3,850	38,450	1	10.8	115	0.00030
Outokumpu-type	1	9,820	9,820	9,820	9,820	10	5.9	49	0.0016
VMS: Felsic	10	60	5,230	1,680	16,790	16	17.7	84	0.011
VMS: Bimodal-mafic	7	80	3,480	1,560	10,950	1	10.1	78	0.0016
VMS: Mafic	14	110	2,260	990	13,860	3	17.4	86	0.0021
Contact-type PGE	19	0.7	60	20	310	6	29.2	82	0.20
Reef-type PGE	24	0.5	360	40	960	0	22.5	75	0.093
All tracts	190	0.5	12,790	1,430	270,970	93	308.9		0.043

N of undiscovered deposits: Mean estimate of the number of undiscovered deposits; Cv of undiscovered deposits: Average coefficient of variation for the number of undiscovedred deposits; -: Not estimated.
Average deposit density values are based on individual tracts. The number of undiscovered Talvivaara-type deposits was estimated assuming an average deposit size of 100 Mt of ore.

Table 6. Known and estimated undiscovered metal resources for different deposit types in Finland.

			At least the indicated amount at the probability of					Mean	Probability of	
	Discovered	Identified	0.95	0.90	0.50	0.10	0.05		Mean or greater	None
Orogenic Au										
Au (t)	339.3	277.3	47	130	750	4,000	6,500	1,600	0.26	0.02
Intrusive Ni-Cu										
Ni (t)	428,709	131,861	28,000	72,000	480,000	2,300,000	3,300,000	890,000	0.31	0.01
Cu (t)	187,495	68,342	13,000	32,000	200,000	930,000	1,300,000	360,000	0.32	0.01
Co (t)	20,314	7,856	1,300	3,400	23,000	110,000	160,000	44,000	0.31	0.01
Komatiitic Ni-Cu										
Ni (t)	42,003	42,003	11,000	39,000	280,000	1,100,000	1,500,000	430,000	0.34	0.02
Cu (t)	7,831	7,831	3,300	10,000	59,000	280,000	410,000	110,000	0.29	0.02
Co (t)	1,698	1,698	400	1,300	10,000	44,000	64,000	18,000	0.31	0.02
Porphyry Cu										
Cu (t)	45,000	45,000	0	35,000	2,400,000	24,000,000	39,000,000	9,300,000	0.25	0.07
Au (t)	14	14	0	1.3	170	2,700	5,400	1,100	0.20	0.07
Ag (t)	100	100	0	9.9	1,000	17,000	37,000	12,000	0.14	0.07
Mo (t)	0	0	0	1,300	100,000	1,100,000	2,100,000	460,000	0.21	0.07
Outokumpu-type										
Cu (t)	1,486,298	216,013	1,200	24,000	580,000	2,100,000	2,600,000	860,000	0.39	0.05
Zn (t)	536,644	116,542	800	13,000	220,000	700,000	900,000	300,000	0.39	0.05
Co (t)	117,616	31,634	170	2,900	53,000	150,000	190,000	68,000	0.41	0.05
Ni (t)	84,252	41,417	230	3,000	41,000	100,000	130,000	49,000	0.43	0.05

VMS										
Cu (t)	872,192	230,570	4,200	35,000	730,000	6,400,000	11,000,000	2,500,000	0.24	0.04
Zn (t)	3,334,781	457,873	14,000	88,000	1,600,000	15,000,000	27,000,000	5,800,000	0.22	0.04
Pb (t)	221,689	89,325	750	6,000	150,000	1,900,000	4,000,000	1,000,000	0.16	0.04
Au (t)	50.8	13	0.19	1.1	16	150	280	68	0.20	0.04
Ag (t)	2,309	748	8.0	56	1,100	12,000	23,000	5,000	0.20	0.04
Contact-type PGE										
Pd (t)	205.9	205.9	110	240	1,600	8,100	12,000	3,200	0.30	0.0136
Pt (t)	51.6	51.6	32	70	430	1,900	2,600	760	0.33	0.0136
Au (t)	26.4	26.4	13	28	160	690	1,000	280	0.31	0.0136
Ni (t)	223,123	223,123	220,000	470,000	2,100,000	5,600,000	7,100,000	2,600,000	0.39	0.0136
Cu (t)	430,303	430,303	340,000	730,000	3,500,000	11,000,000	14,000,000	4,800,000	0.37	0.0136
Reef-type PGE										
Pd (t)	0	0	250	1,300	9,700	44,000	70,000	20,000	0.27	0.032
Pt (t)	0	0	120	590	4,900	26,000	41,000	11,000	0.27	0.032
Au (t)	0	0	6	29	260	1,100	1,600	470	0.31	0.032
Ni (t)	0	0	64,000	350,000	2,100,000	6,900,000	9,100,000	3,000,000	0.36	0.032
Cu (t)	0	0	33,000	170,000	2,100,000	9,500,000	14,000,000	3,800,000	0.32	0.032

Discovered: Total amount of identified resources and cumulative past production; Identified: Remaining identified resources as of 31.12.2013.
Estimated undiscovered resources have been rounded to 2 significant digits.
Resources for undiscovered Talvivaara-type deposits were not calculated, as no grade-tonnage model was available.
Data sources: Rasilainen et al. (2010, 2012, 2014), Eilu et al. (2015), GTK and company reports, news releases and web pages.

Table 7. Percentage of total estimated undiscovered metal resources for each mineral deposit type.

	Cu	Zn	Pb	Ni	Co	Ag	Au	Pd	Pt	Mo
Orogenic Au	-	-	-	-	-	-	54.9	-	-	-
Intrusive Ni-Cu	2.1	-	-	9.6	26.7	-	-	-	-	-
Komatiitic Ni-Cu	0.6	-	-	5.6	11.6	-	-	-	-	-
Porphyry Cu	24.8	-	-	-	-	47.6	12.4	-	-	100
Outokumpu-type	6.0	12.1	-	0.8	61.6	-	-	-	-	-
VMS	7.5	87.9	100	-	-	52.4	1.2	-	-	-
Contact- and reef-type PGE	59.0	-	-	84.0	-	-	31.5	100	100	-

- : Not estimated.
The percentages represent the ratio of the estimated median undiscovered resource for a deposit type to the sum of the median estimated undiscovered resources over all deposit types.

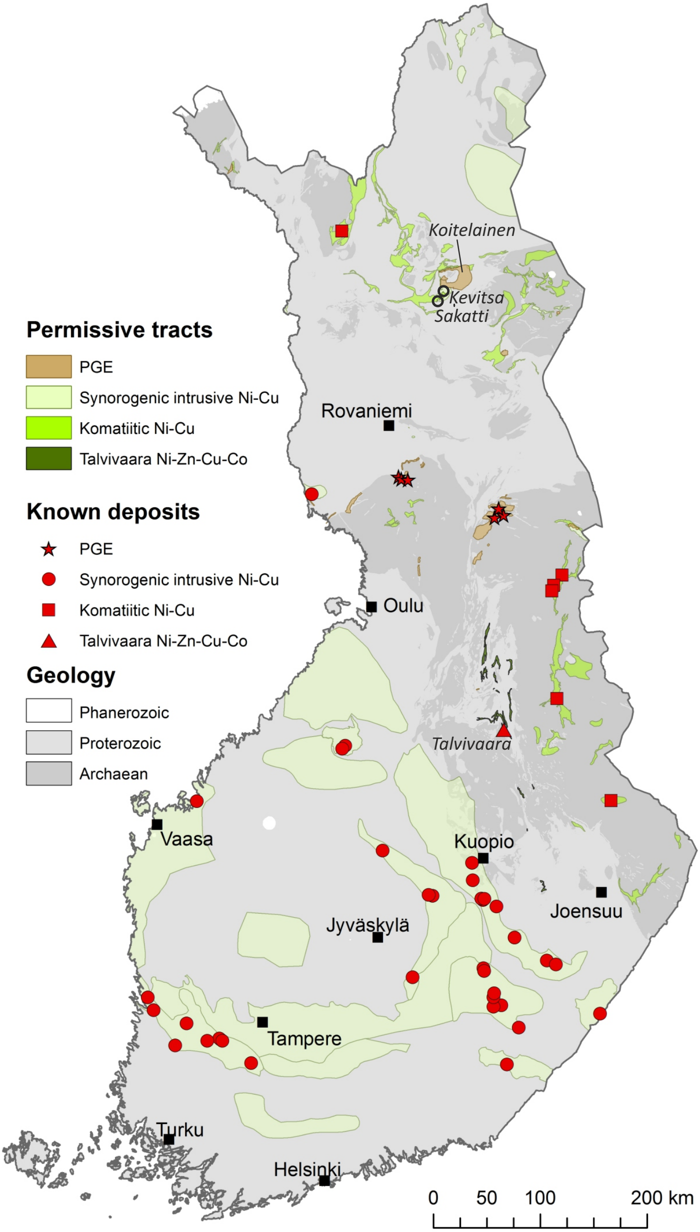

Figure 2. Permissive tracts for layered intrusion-hosted contact- and reef-type PGE deposits and various Ni deposit types in Finland. Known deposits are regarded as well-known and totally delineated, and they are included in the corresponding grade-tonnage model. Locations of the Kevitsa and Sakatti deposits are also shown, although they are not included in the assessment. Black squares indicate main cities.

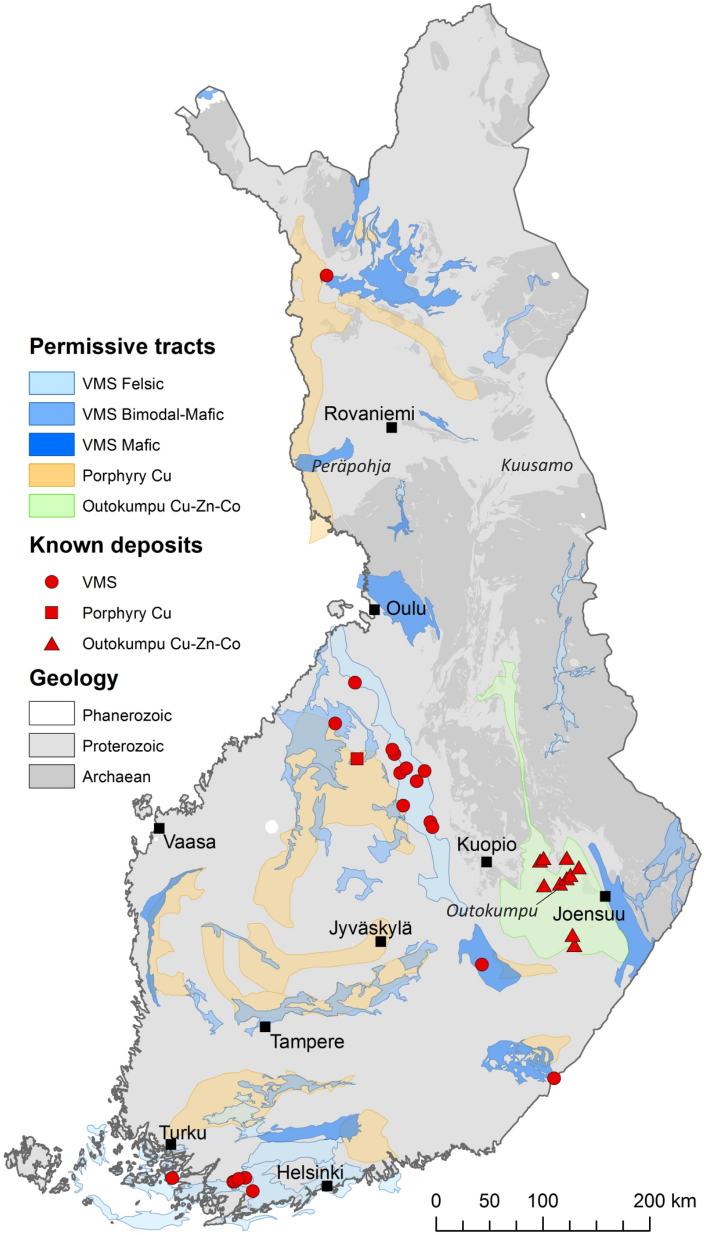

Figure 3. Permissive tracts for VMS, porphyry Cu, and Outokumpu-type deposits in Finland. Known deposits are regarded as well-known and totally delineated, and they are included in the corresponding grade-tonnage model. Black squares indicate main cities.

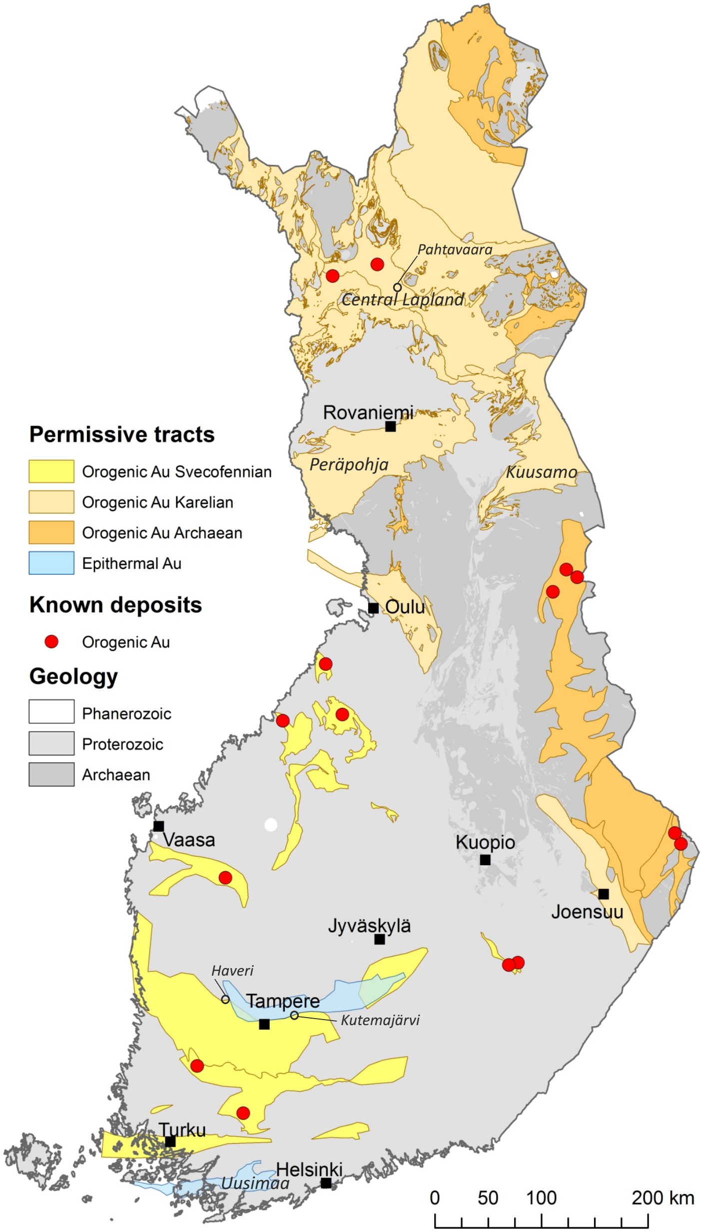

Figure 4. Permissive tracts for orogenic Au deposits in Finland. Known deposits are regarded as well-known and totally delineated, and they are included in the orogenic Au grade-tonnage model. Open circles indicate gold mines whose data were not included in the assessment, as they probably are not of the orogenic type (Table 2). Black squares indicate main cities.

Altogether 190 permissive tracts were delineated for the 10 mineral deposit types included in the assessments (Table 5). The numbers of undiscovered deposits in the tracts were estimated for nine deposit types. The total expected number (mean estimate) of undiscovered deposits for these deposit types is 309 deposits. The metal contents of the undiscovered deposits were assessed for eight deposit types (Table 6) and these results are discussed below.

Platinum and palladium

Most of the discovered platinum-group element resources in Finland are in contact-type PGE deposits hosted by mafic-ultramafic layered intrusions and in the Kevitsa deposit in northern Finland (Table 4). Undiscovered PGE resources in Finland were assessed for layered intrusion-hosted contact- and reef-type PGE deposits. For these two deposit types, enough numerical data from well-explored deposits were available for the construction of grade-tonnage models. The assessment for undiscovered PGE was carried out for the known 2.45 Ga layered intrusions, all of which are located in northern Finland. For the undiscovered resources, 88 % of the Pt and 81 % of the Pd is in reef-type deposits, and the Koitelainen intrusion alone (in Central Lapland, Fig. 2) is estimated to contain 48 % and 44 % of all the undiscovered Pt and Pd, respectively.

We could not estimate undiscovered PGE resources in komatiite-hosted or synorogenic intrusion-hosted Ni deposits due to the lack of sufficient PGE grade data in these deposit types. Furthermore, the limited existing grade (typically <0.1 g/t Pt+Pd) and production data for orogenic intrusive Ni deposits in Finland indicate that the amount of PGE in these deposits is small compared to the Kevitsa deposit and deposits in layered intrusions.

Nickel and cobalt

All the discovered Finnish nickel resources are contained in six types of deposits (Table 4). These are 1) Ni-Cu deposits associated with Svecofennian (1.89–1.87 Ga) synorogenic mafic-ultramafic intrusions in central and southern Finland (Makkonen 2015), 2) Ni-Cu deposits associated with Archaean (ca. 2.8 Ga) komatiitic rocks in eastern and northern Finland and Palaeoproterozoic (ca. 2.05 Ga) komatiitic rocks in northern Finland (Konnunaho et al. 2015), 3) PGE deposits associated with Palaeoproterozoic (ca. 2.45 Ga) mafic-ultramafic layered intrusions in northern Finland, 4) Outokumpu-type polymetallic deposits hosted by 1.97–1.95 Ga ophiolitic ultramafic rocks, 5) the Kevitsa Ni-Cu-PGE deposit, and 6) the Talvivaara-type metamorphosed black shale-hosted Ni-Zn-Cu-Co deposits. Excluding the layered intrusion-hosted PGE deposits, these deposit types also contain the discovered cobalt resources in Finland. No data is available for Co resources in layered intrusion-hosted PGE deposits.

Undiscovered nickel resources in Finland were assessed for layered intrusion-hosted PGE deposits, synorogenic intrusive and komatiitic Ni-Cu deposits and Outokumpu-type deposits. Excluding the layered intrusion-hosted PGE-deposits, undiscovered cobalt resources were assessed for the same deposit types. Permissive tracts were delineated also for the Talvivaara-type deposits, but undiscovered resources in these tracts could not be estimated due to the lack of grade-tonnage data for the Talvivaara type. The overwhelming majority of undiscovered Ni is in layered intrusion-hosted PGE deposits (Tables 6 and 7). Additional, and probably of significantly higher grade, undiscovered Ni resources are in Svecofennian synorogenic mafic-ultramafic intrusions and in komatiite-related deposits. Outokumpu-type deposits contain only a minor part of the undiscovered Ni resources, but appear to contain the majority of the undiscovered cobalt.

Due to the lack of sufficient grade data, we could not assess undiscovered Co resources in layered intrusion-hosted PGE deposits. However, Co typically follows Ni in mafic-ultramafic-hosted sulphide deposits, and the layered intrusion-hosted PGE deposits may contain much larger undiscovered Co resources than any other deposit class in Finland.

Copper, zinc, lead, molybdenum, and silver

Copper and zinc are the main or minor commodities in many types of ore deposits in Finland (Table 4). This subsection covers three important deposit types where copper, zinc or both occur as main commodities: volcanogenic massive sulphide (VMS), Outokumpu-type Cu-Zn-Co, and porphyry copper. VMS and Outokumpu-type deposits have historically been the major sources of Cu and Zn in Finland, but the majority of the present identified resources of these metals are in the Talvivaara and Kevitsa deposits.

Undiscovered Cu ± Zn resources were assessed for VMS, Outokumpu-type and porphyry Cu deposits. VMS deposits were classified according to the associated lithology into mafic, bimodal-mafic and felsic subtypes (Mosier et al. 2009), and undiscovered resources were estimated separately for each subtype (Table 5, Fig. 3). Most of the undiscovered Cu resources in Finland were estimated to be in layered intrusion-hosted PGE deposits and porphyry Cu deposits (Tables 6 and 7). Much smaller volumes, but probably at higher metal grades, are hosted by VMS and Outokumpu-type deposits. VMS deposits contain most of the undiscovered zinc and all of the undiscovered lead resources, whereas all the undiscovered molybdenum resources are estimated to be in porphyry Cu deposits. Undiscovered silver is almost evenly distributed between VMS and porphyry Cu deposits.

Gold

Possibly more than ten genetic types of gold deposits have been detected in Finland (Eilu 2015), but enough data for the construction of a reliable grade-tonnage model exist only for orogenic gold deposits. We delineated two permissive tracts for epithermal gold deposits, covering much of the Uusimaa and Tampere volcanic belts in SW Finland (Fig. 4). However, undiscovered gold resources within these tracts could not be estimated, due to the lack of reliable and consistent grade-tonnage data for Precambrian epithermal deposits. The polymetallic, epigenetic, Au-dominated deposits and occurrences in Central Lapland, Kuusamo, and Peräpohja were included in the assessment as part of the orogenic gold deposit class. The evidence for this inclusion is strongest in Central Lapland, but it is somewhat weaker in the Kuusamo belt and even more so in the Peräpohja belt. Future work may provide strong evidence that the Au-Co±Cu systems of Kuusamo as well as Au-Cu and/or Au±U systems of Peräpohja belong to some other deposit class(es), and our reasoning and the undiscovered orogenic gold resources for these areas should be regarded with caution.

Undiscovered orogenic gold resources were estimated separately for Archaean, Palaeoproterozoic Karelian and Palaeoproterozoic Svecofennian areas. The assessment suggests that more than half of the undiscovered orogenic gold resources are located within permissive tracts in the Palaeoproterozoic Karelian greenstones of central and northern Lapland. Of all the assessed mineral deposit types, orogenic deposits cover slightly more than half of the undiscovered gold. Most of the remaining undiscovered gold resources are estimated to be in layered intrusion-hosted PGE-Ni-Cu and porphyry Cu deposits (Tables 5 and 6).

Although gold is known to occur as a by-product in Outokumpu-type deposits and to a lesser degree in komatiitic Ni-Cu deposits (Table 4), the undiscovered Au resources could not be assessed for these deposit types, due to the very limited gold grade data available.

Summary: Distribution of undiscovered resources

The distribution of the estimated undiscovered resources between the permissive tracts is shown in Figures 5–9. All the undiscovered PGE resources and the majority of the undiscovered Ni, Cu, and Au resources occur in northern Finland. For the PGE, Ni, and Cu this is due to the large possible endowment of the layered intrusion-hosted deposits. For Au, orogenic deposits are responsible for most of the undiscovered resources. Undiscovered Zn resources are more evenly distributed, although somewhat concentrated in central and eastern Finland in the Vihanti–Pyhäsalmi and Outokumpu areas.

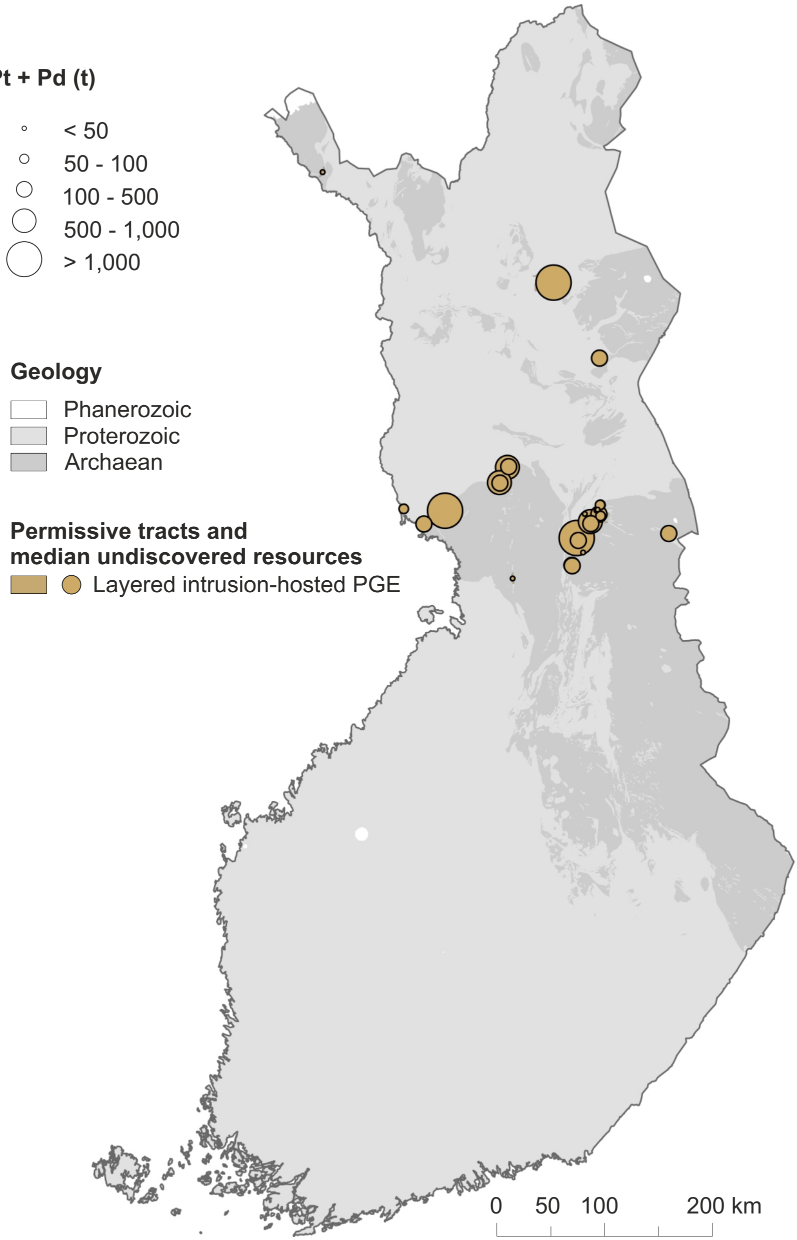

Figure 5. Median estimates of undiscovered PGE resources plotted on permissive tracts. Each symbol corresponds to the estimated metal tonnage for the corresponding tract at the 50 % confidence level. The permissive tracts are very small; hence, the dot indicating the amount of undiscovered Pt+Pd covers most of the tract area.

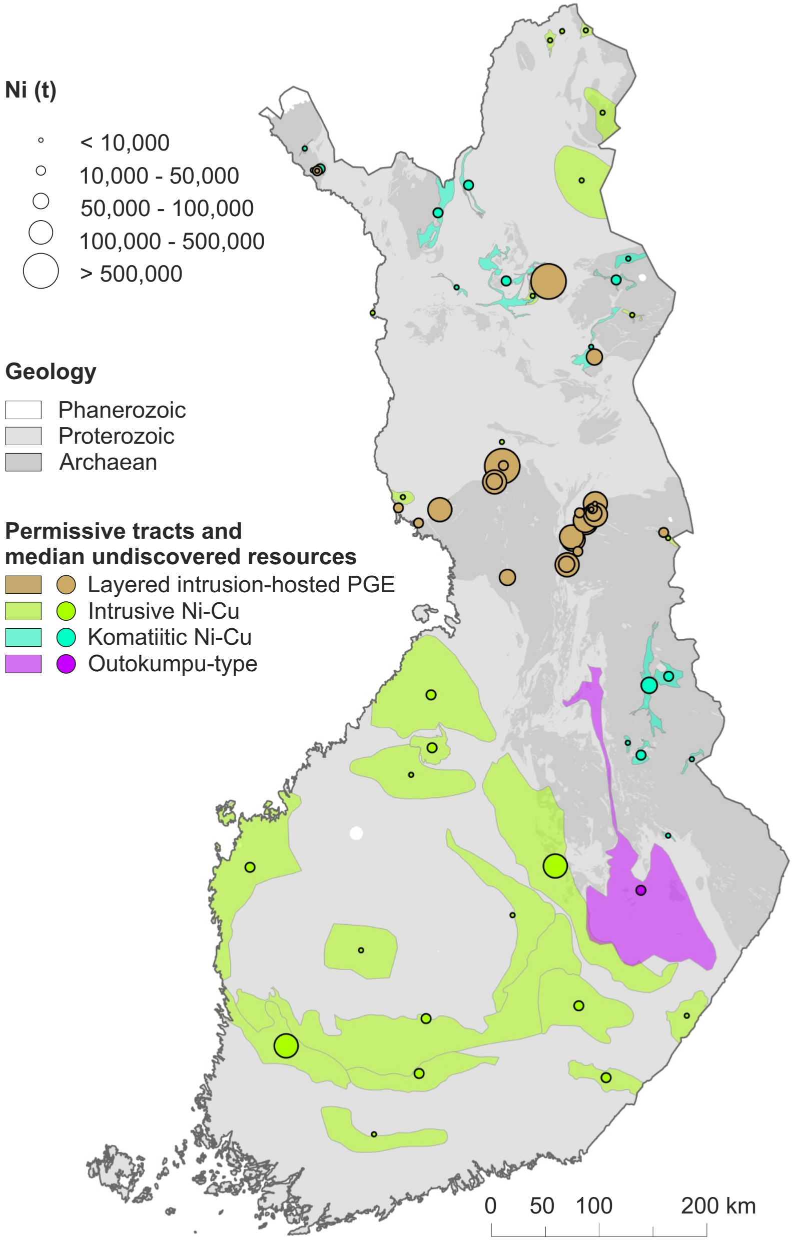

Figure 6. Median estimates of undiscovered Ni resources plotted on permissive tracts. Each symbol corresponds to the estimated metal tonnage for the corresponding tract at the 50 % confidence level.

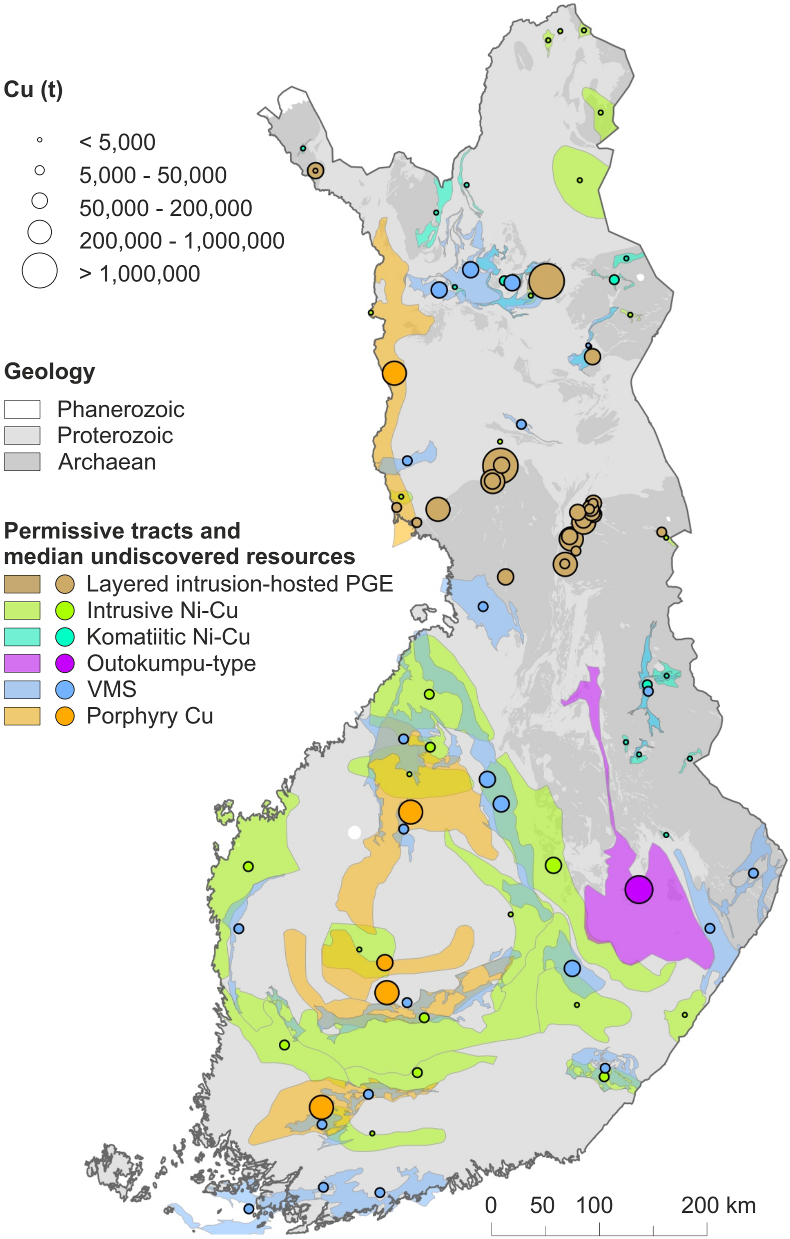

Figure 7. Median estimates of undiscovered Cu resources plotted on permissive tracts. Each symbol corresponds to the estimated metal tonnage for the corresponding tract at the 50 % confidence level.

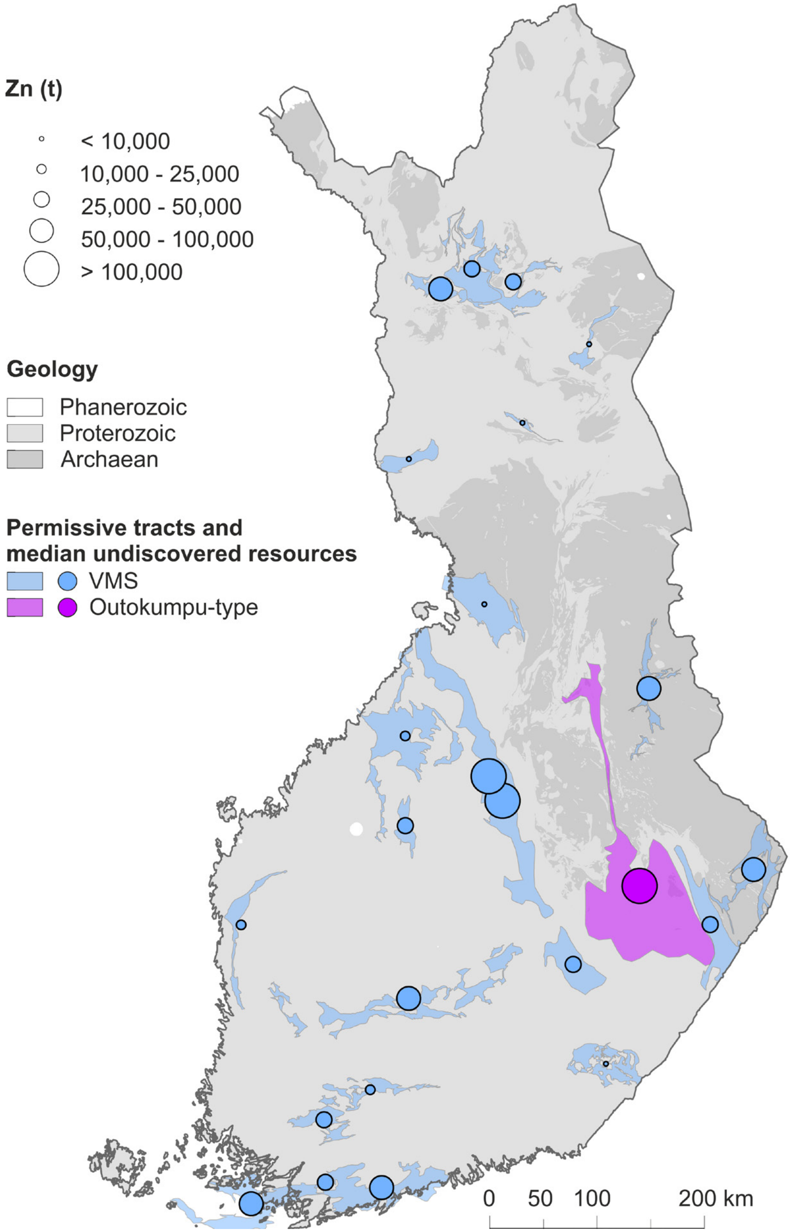

Figure 8. *Median estimates of undiscovered Zn resources plotted on permissive tracts. Each symbol corresponds to the estimated metal tonnage for the corresponding tract at the 50 % confidence level.*

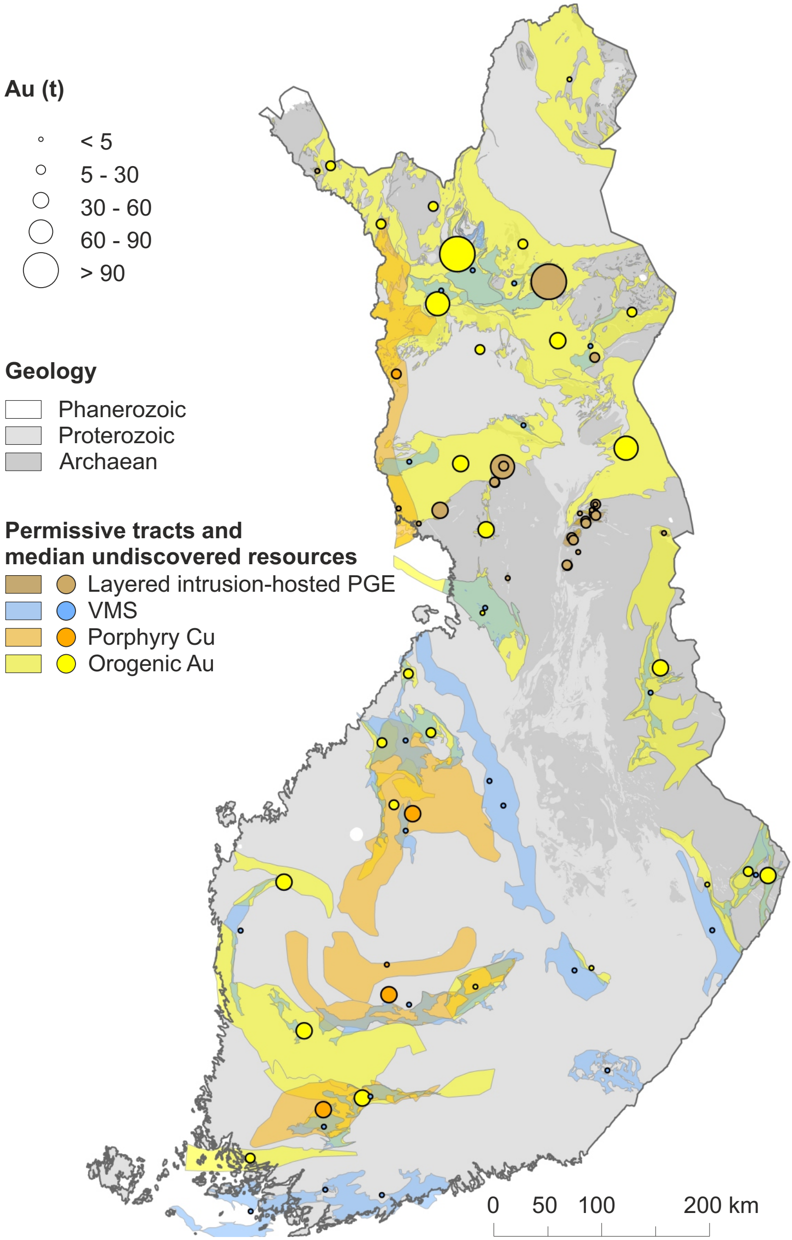

Figure 9. *Median estimates of undiscovered Au resources plotted on permissive tracts. Each symbol corresponds to the estimated metal tonnage for the corresponding tract at the 50 % confidence level.*

References

Briskey, J.A. and Schulz, K.J. (eds.) 2007. Proceedings for a Workshop on Deposit Modeling, Mineral Resources Assessment, and Their Role in Sustainable Development. 31st Int. Geol. Congr., Rio de Janeiro, Brazil, August 18–19, 2000. USGS Circ. 1294. 143 p.

Chorlton, L., Laramee, R., Sinclair, D. and Hillary, E. 2007. Data needs and availability. Digital inventory and mineral deposit geology. USGS Circ. 1294, 101–113.

Duval, J.S. 2012. Version 3.0 of EMINERS – Economic Mineral Resource Simulator. USGS OFR 2004–1344. Available online at: http://pubs.usgs.gov/of/2004/1344.

Eilu, P. 2015. Overview on gold deposits in Finland. In: W.D. Maier, R. Lahtinen, H. O'Brien (eds.) Mineral Deposits of Finland. Elsevier, Oxford. 377–410.

Eilu P., Rasilainen K., Halkoaho T., Huovinen, I., Kärkkäinen N., Kontoniemi O., Lepistö, K., Niiranen T. and Sorjonen-Ward P. 2015. Quantitative assessment of undiscovered resources in orogenic gold deposits in Finland. Geol. Surv. Finland, Rep. Invest. 216. 318 p.

European Commission 2014. Report on critical raw materials for the EU. Report of the ad hoc working group on defining critical raw materials. May 2014. 41 p. Available online at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

Konnunaho, J., Halkoaho, T., Hanski, E. & Törmänen, T. 2015. Komatiite-hosted Ni-Cu-PGE deposits in Finland. In: W.D. Maier, R. Lahtinen, H. O'Brien (eds.) Mineral Deposits of Finland. Elsevier, Oxford. 93–132.

Makkonen, H.V. 2015. Nickel deposits of the 1.88 Ga Kotalahti and Vammala belts. In: W.D. Maier, R. Lahtinen, H. O'Brien (eds.) Mineral Deposits of Finland. Elsevier, Oxford. 253–290.

Mosier, D.L., Berger, V.I., and Singer, D.A., 2009. Volcanogenic massive sulfide deposits of the world; database and grade and tonnage models. USGS OF Rep. 2009-1034. 28 p.

Rasilainen K., Eilu P., Halkoaho T., Iljina M. and Karinen T., 2010. Quantitative mineral resource assessment of nickel, copper, platinum, palladium and gold in undiscovered PGE deposits in mafic-ultramafic layered intrusions in Finland. Geol. Surv. Finland, Rep. Invest. 180. 300 p.

Rasilainen, K., Eilu, P., Äikäs, O., Halkoaho, T., Heino, T., Iljina, M., Juopperi, H., Kontinen, A., Kärkkäinen, N., Makkonen, H., Manninen, T., Pietikäinen, K., Räsänen, J., Tiainen, M., Tontti, M. and Törmänen, T., 2012. Quantitative mineral resource assessment of nickel, copper and cobalt in undiscovered Ni-Cu deposits in Finland. Geol. Surv. Finland, Rep. Invest. 194. 521 p.

Rasilainen K., Eilu P., Halkoaho T., Karvinen A., Kontinen A., Kousa J., Lauri L., Luukas J., Niiranen T., Nikander J., Sipilä P., Sorjonen-Ward P., Tiainen M., Törmänen T. and Västi K., 2014. Quantitative assessment of undiscovered resources in volcanogenic massive sulphide deposits, porphyry copper deposits and Outokumpu-type deposits in Finland. Geol. Surv. Finland, Rep. Invest. 208. 393 p.

Rasmussen, R.O. (ed.) 2011. Megatrends. TemaNord 2011:527. Copenhagen: Nordic Council of Ministers. 205 p.

Root, D.H., Menzie, W.D. and Scott, W.A. 1992. Computer Monte Carlo simulation in quantitative resource estimation. Nat. Resources Res. 1, 125−138.

Singer, D.A. 1993. Basic concepts in three-part quantitative assessments of undiscovered mineral resources. Nonrenewable Resources 2, 69−81.

Singer, D.A,. and Menzie, W.D. 2010. Quantitative mineral resource assessments: An integrated approach. New York: Oxford University Press. 219 p.

USGS NMRA Team 2000. 1998 Assessment of undiscovered deposits of gold, Silver, copper, lead, and Zinc in the United States. USGS Circ. 1178. 22 p.

Wellmer, E.W. & Dalheimer, M. 2012. The feedback control cycle as regulator of past and future mineral supply. Mineralium Deposita 47, 713–729.

GTK assessment work provides statistical estimates for the expected platinum, palladium, nickel, copper, zinc, and gold endowment in undiscovered, but potentially exploitable deposits in the uppermost one kilometre of the bedrock in Finland.