

Quantitative assessment of undiscovered resources in Kuusamo-type Co-Au deposits in Finland

Rasilainen Kalevi, Eilu Pasi, Huovinen Irmeli, Konnunaho Jukka, Niiranen Tero, Ojala Juhani,
Törmänen Tuomo

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GEOLOGICAL SURVEY OF FINLAND

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by

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Cobalt and gold resources in undiscovered Kuusamo-type Co-Au deposits were estimated down to a depth of one kilometre in the bedrock of Finland, using a three-part quantitative assessment method. There are 10 well-known Kuusamo-type Co-Au deposits in Finland, all of which are located within the Palaeoproterozoic Kuusamo schist belt in north-east Finland. The identified resources in these deposits are 22,000 t of cobalt and 19 t of gold. Kuusamo-type deposits are not known elsewhere. Hence, the grade-tonnage model for the assessment was constructed using data on the 10 well-known deposits within the Kuusamo schist belt. Based on the characteristics of the known Kuusamo-type deposits and their geological environment, eight permissive tracts were delineated, mostly in northern Finland. The tracts cover 21,082 km², which is approximately 6% of the total land area of Finland. The expected number of undiscovered deposits within the delineated permissive tracts is 58, and the undiscovered deposits are estimated to contain, with 50% probability, at least 100,000 t of cobalt and 85 t of gold. Approximately 50% of the undiscovered resources are estimated to be located in the Kuusamo and Peräpohja permissive tracts in northern Finland. The assessment results indicate that at least 80% of the remaining Kuusamo-type cobalt and gold endowment within the uppermost one kilometre of the Finnish bedrock is in poorly explored or entirely unknown deposits. The Finnish cobalt resources are very small compared with known global resources, but in a European context they are significant.

Keywords: cobalt, gold, undiscovered resources, evaluation, quantitative analysis, Kuusamo, Proterozoic, Archaean, Finland

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1 INTRODUCTION

Throughout the history of humankind, the demand for mineral resources has increased with the continuing growth in the world's population and the rise in the average material standard of living of an ever-increasing number of individuals. In tandem with this trend, exploration and development of new mineral resources all over the world are facing increasing competition from other land uses (e.g. Briskey et al. 2007, Cunningham et al. 2007, Idman et al. 2007, Rasmussen 2011, World Economic Forum 2014, 2015). Recycling cannot cover the full demand for practically any metal, even when very little of the commodity, such as gold, is lost during production, manufacturing and recycling (e.g. Buchert et al. 2009, Wellmer & Dalheimer 2012). Concerns about the environmental effects of mining are also having a growing influence on the cost and pace of development of new natural resources. In the current global context, Finland is looking into reducing its dependency on the import of raw materials with high supply risk for manufacturing and other industries. This also applies to the entire European Union, which is globally a major net importer of nearly all metallic ores and concentrates (Kauppa- ja teollisuusministeriö 2006, Commission of the European Communities 2008, European Commission 2011, 2014, Soleille et al. 2017). Each country needs to know its mineral resources and how they might be expanded and managed. Essential information includes the location of the known resources,

the location and amount of the possibly existing, but as yet undiscovered, resources and the uncertainty related to their existence. Furthermore, it is important to know how the development of mineral deposits will affect local people and other surrounding resources, such as biological diversity, forests, arable land, air and water (e.g. Tolvanen et al. 2018).

This report provides estimates of the location and amount of mineral resources that could still be found in Finland, given all the deposits that have already been discovered and exploited. It does this by describing the process and results of a quantitative assessment of cobalt (Co) and gold (Au) resources in undiscovered Kuusamo-type Co-Au deposits in Finland. The report consists of two parts. The first part reviews the Kuusamo-type Co-Au deposits in Finland and their geological environments, the assessment method, the data used and the assessment process itself. A summary of the assessment results is given and the results are discussed. The second part comprises the Appendices, which include the deposit models employed and detailed information on each permissive tract delineated.

The information provided here on the location and amount of undiscovered mineral resources is expected to be valuable for effective land-use planning and the sustainable development of mineral resources, and also in evaluating the long-term productivity of investments in exploration and related research and education.

1.1 Assessment project of the Geological Survey of Finland

The demands defined above, and requests from various stakeholders (including the National Audit Office of Finland) to produce exact information on potential resources, resulted in the initiation of an assessment project at the Geological Survey of Finland (GTK) in 2008. The project was established to produce unbiased information on undiscovered mineral resources for national and regional planning of land use, natural resources management and environmental actions, and for improving

assessment tools and their appropriate application in the conditions of Finnish bedrock. The results of the project aim to enable accounting of mineral resources according to the principles of sustainable development. The project also provides new information for metallogenetic and lithological research and for national-level planning of mineral exploration.

The project started in 2008 with the selection of the working methods. By the end of 2018,

undiscovered resources in the following deposit classes in Finland had been assessed: Platinum-group element deposits in mafic-ultramafic layered intrusions (Rasilainen et al. 2010a,b); nickel+copper deposits related to synorogenic mafic-ultramafic intrusions and komatiitic rocks (Rasilainen et al. 2012); volcanogenic massive sulphide, porphyry copper and Outokumpu-type deposits (Rasilainen et al. 2014); orogenic gold deposits (Eilu et al. 2015); stratiform and podiform chromite deposits (Rasilainen et al. 2016), LCT pegmatite-hosted lithium deposits (Rasilainen et al. 2018) and orthomagmatic mafic intrusion-related iron-titanium-vanadium deposits (Rasilainen et al., *in preparation*). The results of the assessment of cobalt and gold resources in Kuusamo-type Co-Au deposits in Finland are provided in this report.

The procedure selected for the GTK assessments is based on a 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 consistent with the present industrial standards such as the JORC, CRIRSCO,

NI 43-101, PERC and UNFC codes (Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy, Australian Institute of Geosciences and Mineral Council of Australia 2012, Committee for Mineral Reserves International Reporting Standards 2013, National Instrument 43-101 2011, Pan-European Reserves and Resources Reporting Committee 2013, United Nations Economic Commission for Europe 2009). The results of undiscovered resource assessments should never be confused with proper reserve or resource estimates based on international standards. Rather, the assessment process produces probabilistic estimates of the total amount of metals *in situ* in undiscovered deposits of selected types, down to a depth of one kilometre. The modification of the process used in the GTK assessments does not take into account the economic, technical, social or environmental factors that might in the future affect the potential for economic utilisation of a resource. Hence, part of the estimated undiscovered resources may be located in sub-economic occurrences (Fig. 1), and it might be more appropriate to use the term ‘metal endowment’, which is not directly dependent on economic or technological factors (Harris 1984).

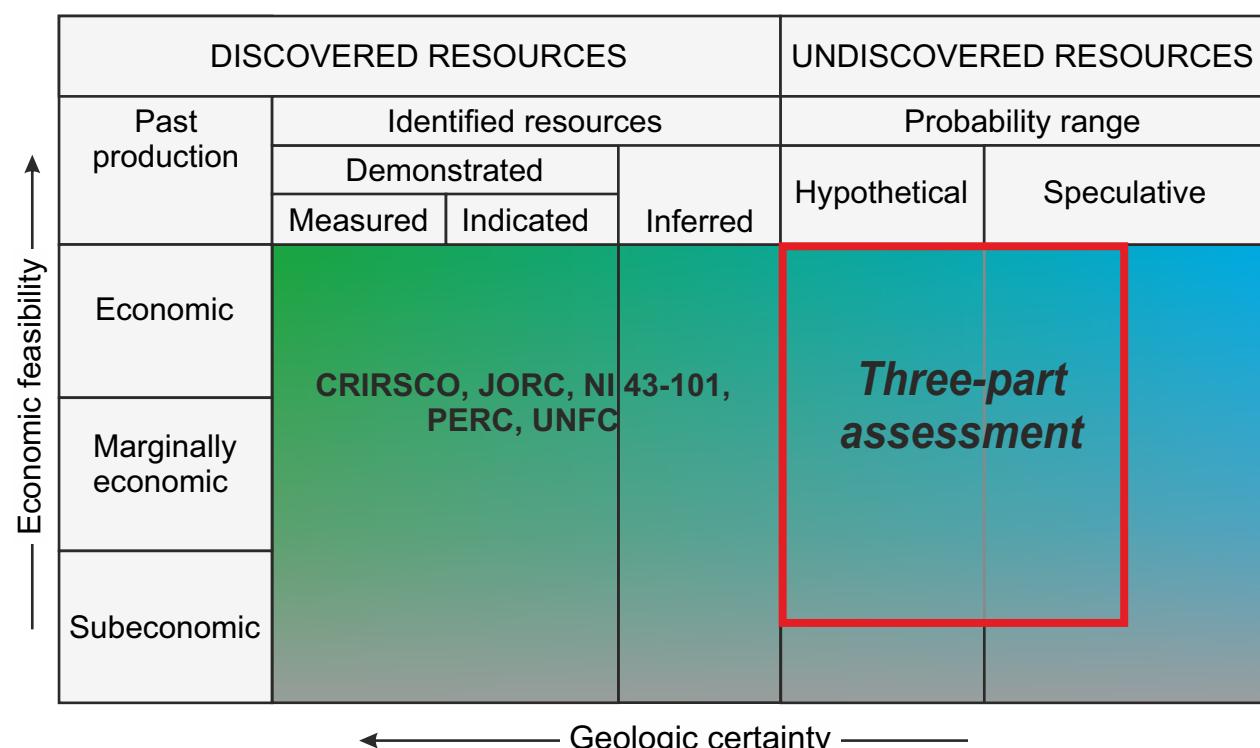


Fig. 1. Classification of mineral resources used in GTK assessments (modified from U.S. Geological Survey National Mineral Resource Assessment Team 2000). Economic feasibility increases upwards and geological uncertainty increases to the right.

1.2 Terminology

Some terms essential to the proper understanding of this report are briefly described below. The definitions follow the usage by the minerals industry and the resource assessment community (U.S. Bureau of Mines and U.S. Geological Survey 1980, U.S. Geological Survey National Mineral Resource Assessment Team 2000, Committee for Mineral Reserves International Reporting Standards 2013).

Mineral deposit

A mineral occurrence of sufficient size and grade that it might, under the most favourable circumstances, be considered to have economic potential.

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 one kilometre 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.

Mineral occurrence

A concentration of any useful mineral found in bedrock in sufficient quantity to suggest further exploration.

Mineral resource

A concentration or occurrence of material of economic interest in or on the Earth's crust in such a form, quality and quantity that there are reasonable prospects for eventual economic extraction.

The location, quantity, grade, continuity and other geological characteristics of a mineral resource are known, estimated or interpreted from specific geological evidence, sampling and knowledge.

Identified resources

Resources whose location, grade, quality and quantity are known or can be estimated from specific geological evidence.

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 unrecognised for their economic potential.

2 COBALT DEPOSITS IN FINLAND

This report presents the results of assessments of undiscovered cobalt and gold resources in Kuusamo-type Co-Au deposits in Finland.

Cobalt is known to occur as a minor commodity in several different types of mineral deposits in Finland (Table 1). However, the majority of the known cobalt endowment in the Finnish bedrock is in synorogenic mafic-ultramafic intrusion-related Ni-Cu deposits, komatiite-related Ni-Cu-PGE deposits,

Outokumpu-type Cu-Co-Zn deposits, Talvivaara-type Ni-Zn-Cu-Co deposits and Kuusamo-type Co-Au deposits. Undiscovered resources of cobalt in the three first-mentioned deposit types in Finland have previously been estimated (Rasilainen et al. 2012, 2014). The undiscovered endowment of cobalt in Talvivaara-type deposits could not be assessed, due to the lack of grade-tonnage information required for construction of a deposit model

(Rasilainen et al. 2010). Large mafic-ultramafic layered intrusions in northern Finland might also contain significant cobalt resources, but the lack

of cobalt grade information prevented estimation of these resources.

2.1 Kuusamo-type Co-Au deposits

Several Palaeoproterozoic greenstone belts in northern Finland display indications of mineralising processes causing cobalt enrichment, or host mineral occurrences enriched in cobalt and having features resembling those of the Kuusamo Co-Au deposits. However, all the well-known Kuusamo-type deposits occur in the Palaeoproterozoic Kuusamo

schist belt in north-east Finland (Fig. 2). Hence, the descriptive model used in this assessment (Appendix 1) was essentially based on the style of mineralisation of the cobalt-gold-copper-bearing deposits and occurrences located in the Kuusamo schist belt.

Table 1. Known cobalt resources in Finland. Only deposits containing at least 1000 t of cobalt are included.

Deposit name	Deposit type	Status	Main metals	Remaining resource Ore (Mt)	Remaining resource Co (t)	Reporting standard
Talvivaara	Talvivaara-type	Active mine	Ni, Co, Zn	1413.8	296,898	JORC
Kevitsa	Magmatic Ni-Cu-PGE	Active mine	Ni,Cu,PGE	311.8	31,180	NI 43-101
Sakatti	Magmatic Ni-Cu-PGE	Not exploited	Ni,Cu	44.4	22,200	JORC
Kylylahti	Outokumpu-type	Active mine	Co,Cu,Ni	7.65	16,830	JORC
Haarakumpu	Kuusamo-type	Not exploited	Co,Cu	4.68	7,956	Historic
Juomasuo Co	Kuusamo-type	Not exploited	Co	5.04	6,048	JORC
Pappilanmäki	Talvivaara-type	Not exploited	Ni,Zn,Co	34.262	4,111	JORC
Ruossakero Ni	Magmatic Ni-Cu-PGE	Not exploited	Ni	35.6	3,560	Historic
Hautalampi	Outokumpu-type	Not exploited	Ni,Co,Cu	3.16	3,476	JORC
Juomasuo Au	Kuusamo-type	Closed mine	Au,Co	2.371	3,082	JORC
Vähäjoki	Iron oxide-copper-gold	Not exploited	Fe,Co,Cu	10.5	3,045	Historic
Saramäki	Outokumpu-type	Not exploited	Co,Cu,Zn,Ni	3.4	2,924	Historic
Perttilahti	Outokumpu-type	Not exploited	Cu,Co,Zn,Ni	1.324	2,118	Historic
Pahtavuoma Zn	VMS	Closed mine	Cu,Zn,Co	21.1	2,110	Historic
Rajapalot	Uncertain (not enough data)	Not exploited	Au,Co	4.257	1,841	NI 43-101
Meurastuksens-aho	Kuusamo-type	Not exploited	Co,Au	0.892	1,784	JORC
Laukunkangas	Magmatic Ni-Cu-PGE	Closed mine	Ni,Co	5.912	1,774	Historic
Kouvervaara	Kuusamo-type	Not exploited	Co,Cu,Au	1.58	1,580	Historic
Ruimu	Magmatic Ni-Cu-PGE	Not exploited	Ni,Co,Cu	3.5	1,400	Historic
Kaukua	Magmatic Ni-Cu-PGE	Not exploited	PGE,Ni,Cu	23.6	1,392	NI 43-101
Haukiaho	Magmatic Ni-Cu-PGE	Not exploited	Ni,Cu,PGE	23.2	1,322	NI 43-102
Saattopora Cu	Polygenetic	Not exploited	Cu,Ni	11.6	1,160	Historic
Vuonos Cu	Outokumpu-type	Closed mine	Cu,Co,Zn,Ni	0.76	1,140	Historic
Sääksjärvi Ni	Magmatic Ni-Cu-PGE	Not exploited	Ni,Co,Cu	3.5	1,050	Historic
Karhujupukka	Mafic intrusion-hosted Ti-Fe±V	Not exploited	V,Fe,Ti	5.2	1,040	Historic
Luikonlahti	Outokumpu-type	Closed mine	Co,Cu,Ni	0.85	1,020	Historic
Total				1,984	422,043	

Mt: Million metric tons; t: metric ton. Data sources: Rajapalot - Mawson Resources (2018), other deposits - FODD (2018).

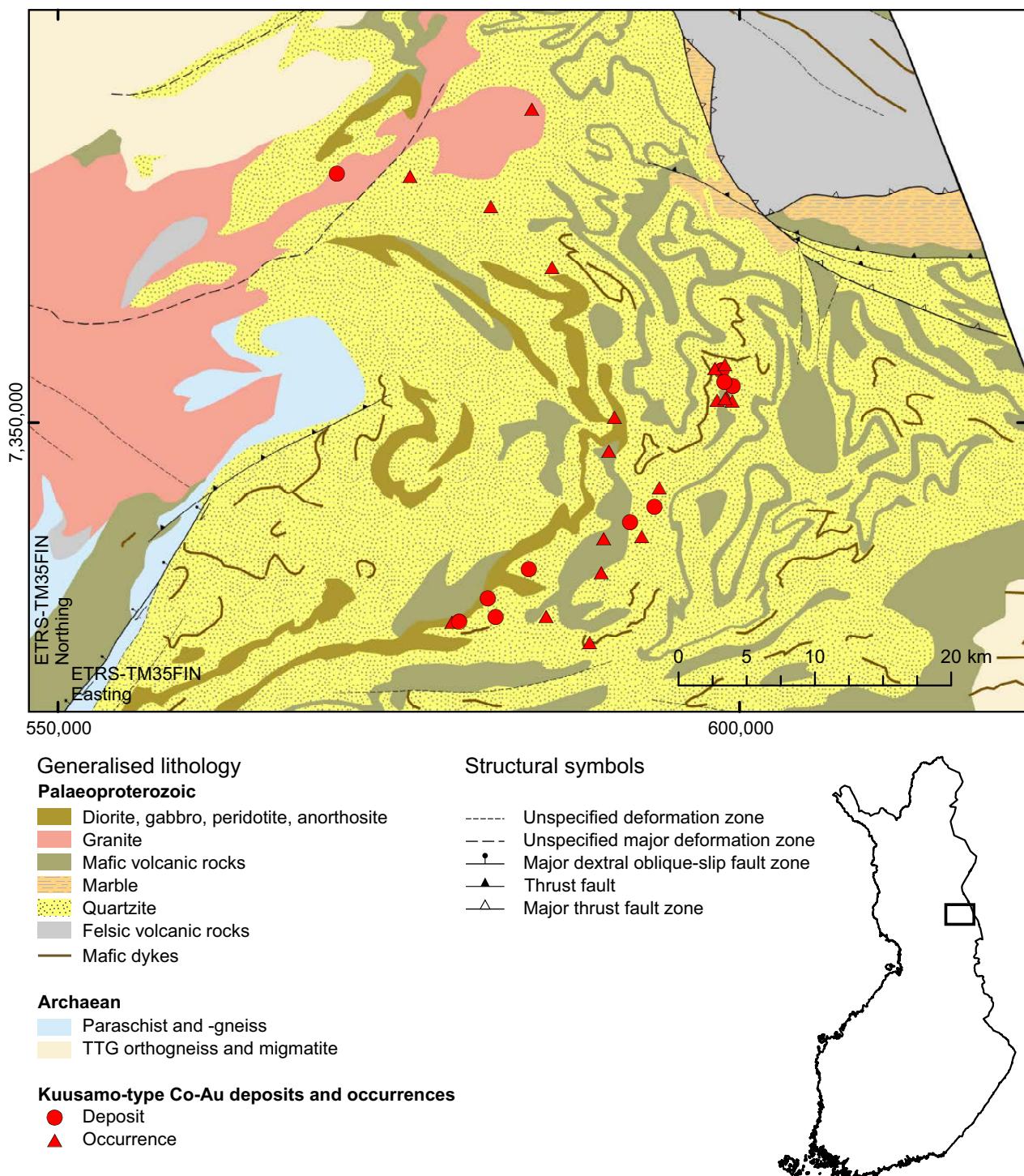


Fig. 2. Generalised geology of the central part of the Kuusamo schist belt, with the known Au-Co deposits and occurrences. The geological map is based on the GTK in-house digital bedrock database (Bedrock of Finland – DigiKP).

There are dozens of gold deposits and occurrences in Finland that resemble typical orogenic gold deposits in all other features, but are atypical because they contain silver, copper, cobalt, nickel or antimony as potential commodities in addition to gold. Such occurrences can be classified as “Orogenic gold with atypical metal association”. In

addition to pyrite, pyrrhotite and/or arsenopyrite, they may include significant amounts of chalcopyrite, cobaltite, pentlandite, gersdorffite and/or stibnite (Vanhainen 2001, Eilu et al. 2007, Eilu 2015). Goldfarb et al. (2001, 2005) suggest that orogenic gold deposits with an atypical metal association formed where Palaeoproterozoic tectonism included

deformation of older, intracratonic basins. The resulting ore fluids were anomalously saline and produced base-metal rich orogenic gold deposits, such as in the Kaapvaal craton of South Africa and the Arunta, Tennant Creek and Pine Creek areas of northern Australia.

It is possible that such deposits reflect mobilisation of basinal fluids under moderate to high-grade metamorphic conditions (Yardley & Graham 2002, Yardley & Cleverley 2013), with the metals possibly (but not necessarily) enriched prior to an orogeny in the fluid source areas by, for example, seafloor hydrothermal and/or diagenetic processes. In such settings, mineralising fluids are claimed to be able to migrate over 10s to 100s of km in response to collisional tectonics, which drive the fluids basinward from the foreland fold and thrust belts (Yardley & Bodnar 2014).

A similar crustal evolution characterises the Karelian domain of Finland, where supracrustal sequences, possibly including evaporates, formed in intracratonic basins between 2.45 and 1.95 Ga (Perttunen & Vaajoki 2001, Rastas et al. 2001, Lahtinen et al. 2005, 2012, Skyttä et al. 2019). They were episodically intruded by magmas, locally resulting in alteration of the supracrustal rocks prior to regional metamorphism. It even seems possible that some (currently uneconomic) local base metal ± gold enrichment occurred before the orogeny. The extensive albitisation and carbonatisation in the Kuusamo, Peräpohja and Central Lapland belts, the Alta-Kvaenangen area in northernmost Norway, the Onega basin in the eastern Russian Karelia and the regional scapolitisation in northern Finland and northern Sweden are claimed to be the result of such preorogenic processes (Eilu 1994, Vanhanen 2001, Kyläkoski 2009a,b, Billström et al. 2010, Melezhik et al. 2013, 2015). In addition, Palaeoproterozoic halite, magnesite and dolostone units of distinctly evaporitic origin, in a sequence of a similar age to that hosting the Kuusamo Au-Co deposits, have been detected in the Onega basin, in the eastern part of the Fennoscandian shield (Melezhik et al. 2013).

The Kuusamo schist belt (KuSB) is characterised by Au-Co ± Cu ± U ± LREE mineralisation (Pankka 1992, Pankka & Vanhanen 1992, Vanhanen 2001). The reported tonnage and gold, cobalt and copper grades of the deposits in the belt show considerable variation (Appendix 2, Table 1). In a few cases, the resource also includes 0.01–0.03% U and 0.02–0.1% total rare earth elements (REE) (Vanhansen 2001, Dragon Mining 2013). The main economic interest in

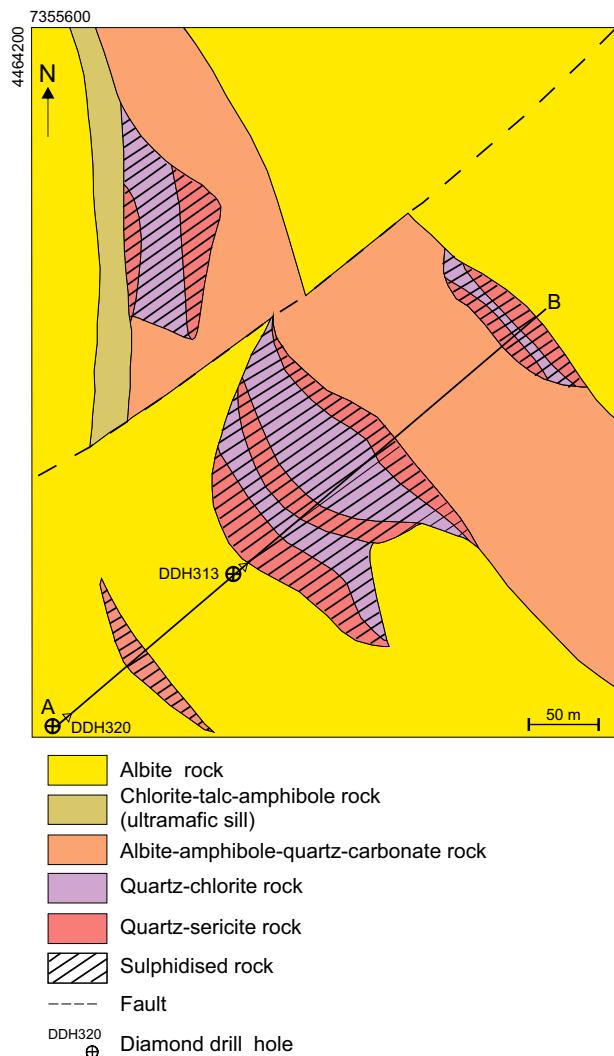


Fig. 3. Juomasuo surface geology. Modified after Vanhanen (2001).

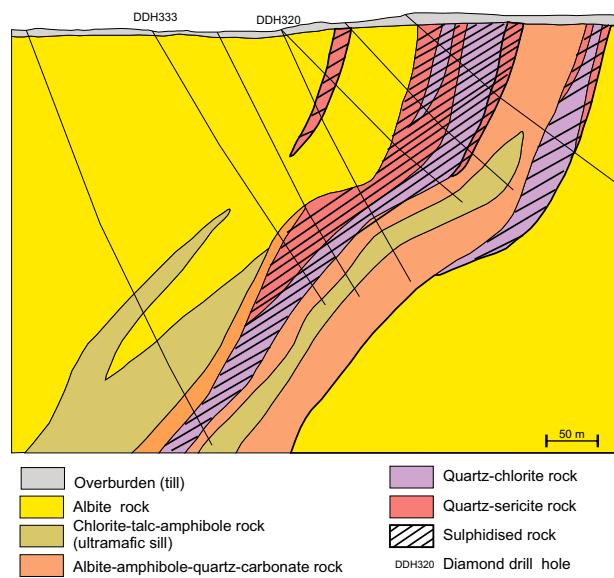


Fig. 4. Juomasuo cross-section. Modified after Vanhanen (2001).

the Kuusamo deposits is in gold and cobalt, whereas copper and REE are regarded as potential by-products and uranium as a problematic waste product (Dragon Mining 2013). The available detailed data, mainly from Vanhanen (2001), suggest that most of the reported total REE grades in these occurrences comprise light rare earth elements (LREE). None of the KuSB occurrences has so far been proven to comprise economic ores, and only one (Juomasuo) has been test mined, in 1992, when 104 kg gold and 24.7 t cobalt were extracted from 17,635 t of ore (Puustinen 2003) (Figs. 3 and 4).

The Kuusamo occurrences are hosted by a clastic sedimentary-dominated sequence deposited between 2.35 and 2.21 Ga, which also contains basaltic lavas and indications of evaporates (Vanhainen 2001). The sequence was intruded by basaltic dikes and sills prior to regional deformation. All occurrences have a distinct structural control; most of them are hosted at the intersections of a regional northeast-trending anticline with northwest-trending faults. The largest deposit, Juomasuo, is located in a doubly-plunging part of the north-east trending anticline.

Alteration in the KuSB is extensive and occurred at several stages. The rocks in the belt were affected by three regional and at least one localised alteration event (Pankka 1992, Pankka & Vanhanen 1992, Vanhanen 2001): (1) diagenetic, partial albitisation of feldspars and sericitisation of clay minerals in all sedimentary units; (2) local, partial to total albitisa-

tion of clastic sedimentary units and spilitisation of volcanic units, either related to the ~2.21 Ga intrusion of the mafic sills and dikes, or the early stages of subsequent orogenic evolution; (3) overprinting of the early spilitisation and albitisation by much more extensive albite and scapolite alteration and local carbonatisation (Fig. 5); and (4) localised, weak to intense sulphidation with K ± Fe, Mg alteration in possibly two or more substages. The intensity of the last regional alteration (stage 3) varied from weak (<10 vol% albite) to strong, locally resulting in almost pure albite rocks (99 vol% albite, with traces of carbonate, rutile and quartz). Metallic mineralisation (Au-Co ± Cu ± U ± LREE) appears to relate clearly to the stage 4 alteration (Vanhainen 2001).

Syndiagenetic, alkaline, high-salinity oxidising fluid activity has also been proposed for a clastic sedimentary sequence, 2.3–2.1 Ga in age, located in a rifted craton margin setting a few hundred km to the south of Kuusamo (Lahtinen et al. 2013). Such fluids can aggressively alter the rocks with which they interact, as indicated by the disturbed REE patterns in the area (Lahtinen et al. 2013). In addition to the regional alteration, local alteration surrounding and hosting the metallic mineralisation in the KuSB includes carbonatisation, sericitisation, biotitisation and sulphidation. The deposits are enriched in As, Au, Bi, Co, CO₂, Cu, K, LREE, Mo, Rb, S, Se, Te, U, and W, and somewhat less enriched in Fe, heavy REE (HREE), Mn, Mo, Ni, Pb, and Th. The Au/Ag ratio is consistently higher than



Fig. 5. Albitisation front in metasiltstone at Juomasuo. Intense albitisation is causing replacement of all the other major silicates, but the primary layering is still weakly visible in the albitised part. The compass plate is 11 cm long. Photo by Pasi Eilu (2006).

1 (Pankka 1992, Vanhanen 2001, Vasilopoulos 2015). The deposits are always hosted, or at least enveloped by, albited and carbonated rocks, but there is commonly a depletion of Na and Ca in the ore itself compared with host rocks. The latter chemical changes are clearly related to the localised, syn-orogenic, stages of alteration and mineralisation (Vanhansen 2001).

The main ore minerals in the KuSB deposits are cobaltian pyrite, pyrrhotite, cobaltite, cobaltian pentlandite and chalcopyrite. Native gold occurs in free form within gangue and also associated with bismuth and tellurium minerals that are present as inclusions and in fractures in pyrite, pyrrhotite, cobaltite, and uraninite (Pankka 1992, Vanhanen 2001).

The metallic occurrences in the KuSB have historically been classified into various deposit classes, including orogenic gold with atypical metal association, iron-oxide-copper-gold (IOCG), Blackbird-type and syngenetic (e.g. Pankka 1992, Pankka & Vanhanen 1992, Vanhanen 2001, D. I. Groves, personal communication 2006, Slack et al. 2010, Slack 2013). No exactly similar deposits have yet been discovered elsewhere in Finland or in other countries; therefore, they are classified here as "Kuusamo-type". However, there are some similarities with some of the gold deposits in the Peräpohja belt, 200 km to the west of Kuusamo (Ranta et al. 2018).

Most of the available evidence suggests a late-orogenic, post-peak metamorphic, timing of metallic mineralisation and the related localised alteration, at two or more stages in 1.85–1.81 Ga (Mänttäri 1995, Vanhanen 2001, Pohjolainen et al. 2017). The timing of mineralisation in the KuSB seems to be consistent with both the orogenic gold and Blackbird-type deposit models. Alteration style, metal association and the nature of the mineralising fluid(s) fit best with the Blackbird-type model, mostly also with the IOCG class. The nature of the mineralising fluid(s), the metal association and the rift-shelf setting are consistent with features

of a Blackbird-type model, but also with orogenic gold with an atypical metal association. Structural control and gold fineness are not uncharacteristic of any of the proposed models. The Kuusamo deposits were classified into the IOCG category by Vanhanen (2001). However, the deposits contain no iron oxides, nor are there obvious epigenetic oxide iron deposits in the vicinity.

Most of the data suggest that the KuSB deposits are epigenetic and that pre-metamorphic alteration prepared the ground by making soft rocks harder and more competent, with the early basinal circulation providing brines to transport the metals. Overall, the deposit characteristics are most consistent with the orogenic gold model with an atypical metal combination. The main issues in not including the Kuusamo deposits in *sensu lato* orogenic gold class include the multiple stages of alteration, the extensive mobility of most metals in the mineralising system and the metal zoning within the deposits (Fig. 6).

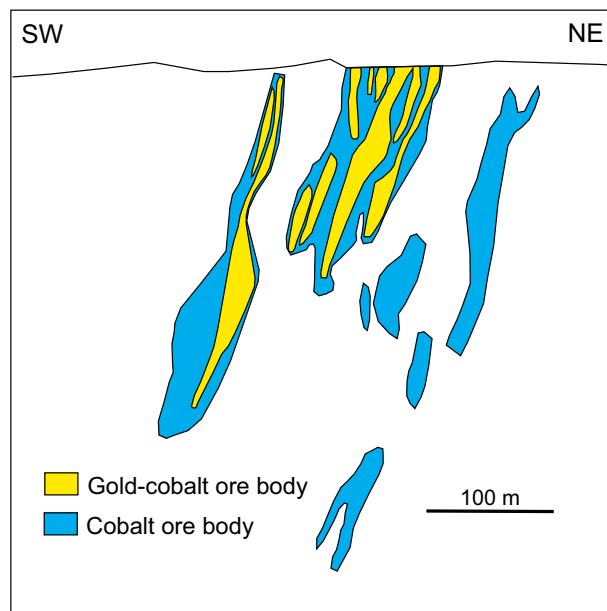


Fig. 6. Metal zoning at Juomasuo, as defined in a resource model by Dragon Mining (2014).

3 THE THREE-PART QUANTITATIVE RESOURCE ASSESSMENT METHOD

Numerous methods have been developed and applied to the estimation of undiscovered mineral resources during the past decades, but the task still remains challenging and there is no universally accepted, definitive procedure (e.g. Lisitsin et al. 2007 and references therein). Published methods for quantitative mineral resource assessment include the three-part approach (Singer & Menzie 2010), Zipf's law approach (Rowlands & Sampey 1977, Merriam et al. 2004, Mamuse & Guj 2011), regression-based techniques (Mamuse et al. 2010), one-level assessment (McCammon & Kork 1992, McCammon et al. 1994) and various combinations of these (e.g. Chudasama et al. 2018). The three-part approach is the most widely used method for quantitative assessment of undiscovered mineral resources, and it was also selected as the method for GTK assessments.

The three-part quantitative assessment method was developed at the USGS starting from the mid-1970s (Singer 1975, Cox & Singer 1986, Root et al. 1992, Harris et al. 1993, Barton et al. 1995, Singer 1993, Drew 1997, Singer & Menzie 2010). It has been increasingly used by the USGS and others since 1975 (e.g. Richter et al. 1975, Singer & Overshine 1979, Drew et al. 1984, Bliss 1989, Brew et al. 1992, Box et al. 1996, U.S. Geological Survey National Mineral Resource Assessment Team 2000, Kilby 2004, Lisitsin et al. 2007, 2014, Cunningham et al. 2008, Hammarstrom et al. 2010, 2013, 2014, Rasilainen et al. 2010a, 2012, 2014, Mihalasky et al. 2011, 2015a,b,

Box et al. 2012, Ludington et al. 2012a,b, Sutphin et al. 2013, Cossette et al. 2014, Gray et al. 2014, Zientek et al. 2014a,b,c, 2015a,b, Zürcher et al. 2015, Wynn et al. 2016, Cocker et al. 2017). The method was considered well suited to accomplishing the goal of the GTK assessment project to estimate the undiscovered mineral endowment in Finland. The assessment is based on the statistical methods of data analysis and integration and it treats and expresses uncertainty. The method enables the use of varying amounts of objective geological data and subjective expert knowledge and it generates reproducible assessment results.

The three-part method consists of the following components: (1) evaluation and selection or construction of descriptive models and grade-tonnage models for the deposit types under consideration; (2) delineation of areas according to the types of deposits permitted by the geology (permissive tracts); and (3) estimation of the number of undiscovered deposits of each deposit type within the permissive tracts. The estimated number of deposits is combined with the grade and tonnage distributions from the deposit models to assess the total undiscovered metal endowment. In addition to the three components, the process flow of a typical assessment project applying the three-part method contains one or more data gathering phases (Fig. 7). The parts of the method are described in more detail in sections 3.1–3.4.

3.1 Deposit models

Deposit models designed for quantitative assessments are the cornerstone of the method. They are used to classify mineralised and barren environments, as well as types of known deposits, and to discriminate mineral deposits from mineral occurrences (Singer & Berger 2007). Deposit models that can be used in the three-part assessment method include descriptive models, grade-tonnage models, deposit density models, economic models and quantitative descriptive models. Descriptive models and grade-tonnage models are an essential component of the three-part method and they were used in all GTK assessments. Deposit density models, when available, can be used in estimation of the number of undiscovered deposits for an area. Economic

models and quantitative descriptive models were not used in the GTK assessment project.

3.1.1 Descriptive models

A descriptive model consists of systematically arranged information describing all the essential characteristics of a class of mineral deposits (Barton 1993). A descriptive model usually consists of two parts. The first part describes the geological environments in which the deposits occur. It contains information on favourable host rocks, possible source rocks, age ranges of mineralisation, the depositional environment, tectonic setting and associated deposit types. This part of the descriptive

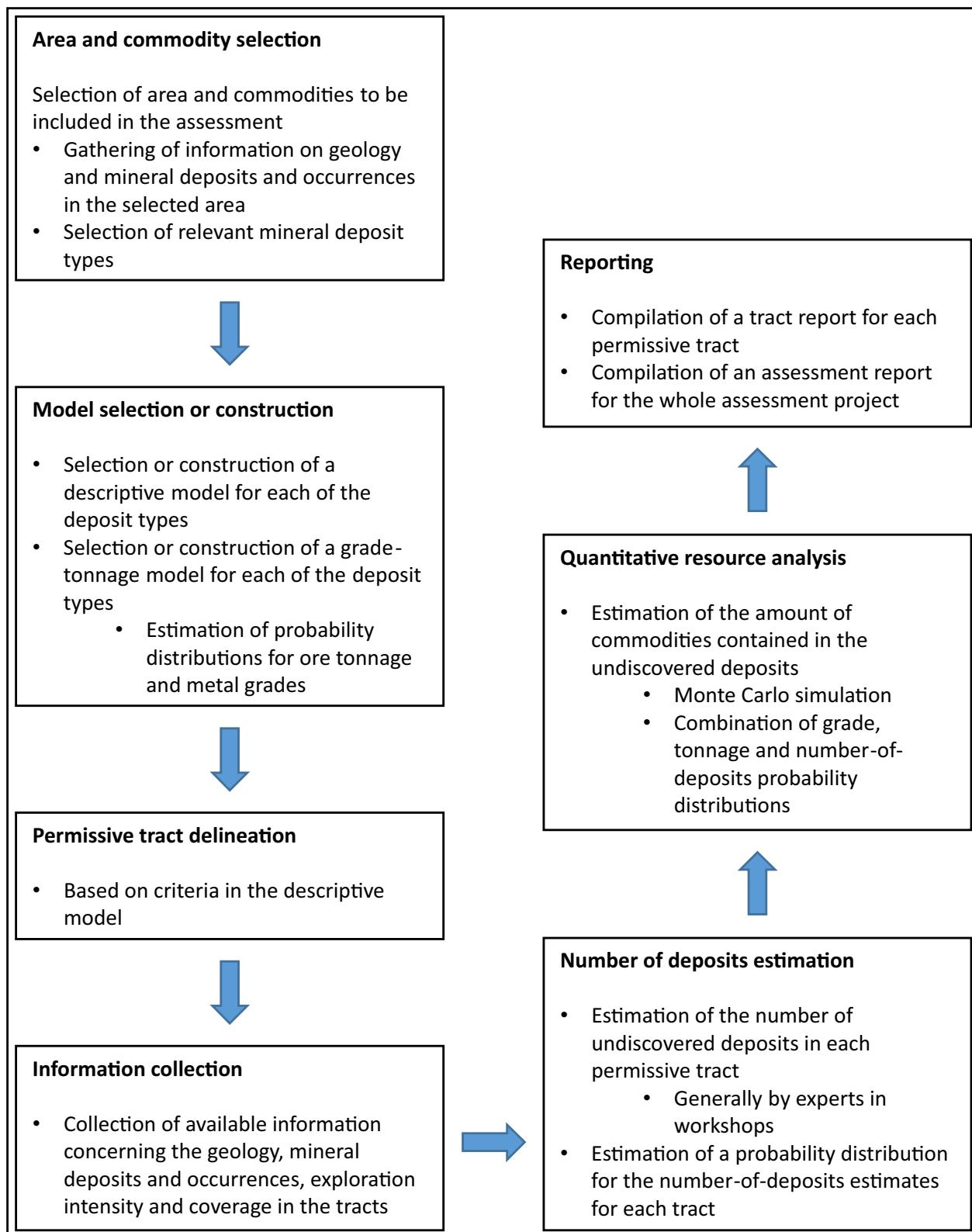


Fig. 7. Process flow of a typical three-part assessment project.

model plays a crucial role in the delineation of permissive tracts, i.e. areas where the geology permits the occurrence of deposits of the type under consideration.

The second part of a descriptive model lists the essential identifying characteristics by which a given deposit type might be recognised. These include ore textures and structures, mineralogy, alteration, and geochemical and geophysical signatures. The second part of the model is used to classify known deposits and occurrences. Identifying the types of known deposits is important for the tract delineation process, and it can sometimes help to delineate geological environments not indicated on geological maps.

3.1.2 Grade-tonnage models

A grade-tonnage model consists of data on average metal grades and the associated total tonnage of well-studied and completely delineated deposits of a certain type (Singer 1993, Singer & Menzie 2010). The total tonnage combines total past production and current resources (including reserves) at the

lowest possible cut-off grade. Grade-tonnage models are usually presented as frequency distributions of tonnage and average metal grades. These distributions are used as models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings. They also help in differentiating between a deposit and a mineral occurrence, and in judging whether a deposit, or group of deposits, belongs to the type represented by the model.

It is very important to use the same sampling unit criteria for all deposits in the grade-tonnage model. Mixing old production data from some deposits with resource data from other deposits is among the most common errors in the construction of grade-tonnage models and will produce biased models (Singer & Berger 2007). Spatial aspects of the sampling unit must also be considered. A spatial rule identifying the minimum distance between two separate deposits of a given type should be defined, and deposits closer to each other than the minimum distance should be combined in the grade-tonnage model.

3.2 Permissive tracts

A permissive tract is an area on the Earth's surface within which the geology permits the existence of mineral deposits of one or more specific types (Singer 1993, Singer & Menzie 2010). As permissive rocks also occur at depth, a permissive tract actually represents the surface projection of a volume of rock, in which geology allows the existence of deposits. An assessment depth of one kilometre is commonly used as the lower boundary of the permissive volume that is projected on the surface. Geophysical information and structural interpretations can be used to deduce the existence of permissive rocks at depth.

It is important to distinguish between areas favourable for the existence of deposits and permissive tracts: the former are a subset of the latter. The presence of a permissive tract in an area does not specify the level of favourability for the occurrence of deposits within the area; it only indicates the possibility of the existence of deposits.

Furthermore, the existence of a permissive tract does not specify the likelihood of discovery of existing undiscovered deposits in the area.

In the three-part assessment method, permissive tracts should be based on criteria derived from descriptive models. Tract boundaries should be defined so that the likelihood of deposits occurring outside of the tract is negligible. The boundaries of the tracts are first defined based on mapped or inferred geology. Tracts may or may not contain known deposits. The existence of deposits is used to confirm and extend the tracts, but the lack of known deposits is not a reason to exclude any part of a permissive area from the tract. Original tract boundaries should only be reduced when it can be firmly demonstrated that a deposit type could not exist. This evidence could be based on geology, knowledge of unsuccessful exploration or the presence of barren overburden exceeding the predetermined delineation depth limit.

3.3 Estimation of the number of undiscovered deposits

The third part of the three-part assessment method is estimation of the number of undiscovered deposits

of the type(s) that may exist in the delineated tracts (Singer 1993, Singer & Menzie 2010). The estimates

represent the probability that a certain fixed, but unknown, number of undiscovered deposits exist in the delineated tracts. The estimates are carried out according to the deposit type and they must be consistent with the grade-tonnage models. This means that, for example, about half of the estimated undiscovered deposits should be larger than the median tonnage given by the grade-tonnage model, and about 10% of the estimated deposits should be larger than the 90th percentile of the model. The spatial rule used to define a deposit in the grade-tonnage model must be respected in the estimates. Well-explored and completely delineated deposits, for which published grade and tonnage values exist, are considered as discovered deposits, whereas deposits without publicly available grade and tonnage information, partly delineated deposits and known occurrences without reliable grade-tonnage estimates are counted as undiscovered.

Several methods can be used either directly or as guidelines to make the estimates. These include the frequency of deposits in well-explored geologically analogous areas (deposit density models), local deposit extrapolations, counting and

assigning probabilities to geophysical and/or geochemical anomalies, process constraints, relative frequencies of associated deposit types and limits set by the total available area or total known metal (Singer 2007). Some of these methods produce a single estimate of the expected number of deposits; others produce a probability distribution of the expected number of deposits. In the latter case, the spread of the estimates for the number of deposits associated with high and low quantiles of the probability distribution (for example, the upper and lower 10-quantiles) indicates the uncertainty of the estimate. The expected number of deposits, or the estimated number of deposits associated with a given probability level, measures the likelihood of the existence of a deposit type.

The estimates are typically made by a team of experts knowledgeable about the deposit type and the geology of the region. The process follows the Delphi technique (Dalkey 1967, Sackman 1974, Rowe & Wright 1999), in which each expert makes an estimate independently and all the estimates are then discussed to possibly reach a final consensus estimate.

3.4 Statistical evaluation

The three parts of the assessment method described above produce consistent estimates of the number of undiscovered deposits for the delineated areas and of the probability distribution of grades and tonnages of the deposit type (Singer & Menzie 2010). As the final step of the assessment, these

estimates are combined using statistical methods to achieve probability distributions of the quantities of contained metals and ore tonnages in the undiscovered deposits. Software using Monte Carlo simulation has been developed for this purpose (Root et al. 1992, Duval 2012, Ellefsen 2017, Shapiro 2018).

4 ASSESSMENT OF KUUSAMO-TYPE CO-AU RESOURCES IN FINLAND

4.1 Resources covered by the assessment

Here, we report the results of the assessment of cobalt resources in undiscovered Kuusamo-type Co-Au deposits in Finland.

4.2 GTK assessment process

The assessment process started with the selection of experts for the assessment team. As the work was conducted as a GTK internal project, only individuals employed by GTK were assigned. Scientists based in GTK offices in northern Finland (n=5) and southern Finland (n=2) were included in the assessment team. The work started with a workshop on 6 April 2018, in which the deposit type to be assessed

was defined and criteria for the delineation and the location of the permissive tracts were discussed. Responsibilities for the delineation and documentation of initial permissive tracts and for the construction of a grade-tonnage model Kuusamo-type Co-Au were assigned to the assessment team members.

After the first workshop, the work continued with the delineation of preliminary permissive tracts, the preparation of tract description documents and the development of descriptive and grade-tonnage models for the Kuusamo-type Co-Au deposits. Assessment of the number of undiscovered deposits within the delineated permissive tracts was carried

out in two successive workshops, on 29 May and 14 August 2018.

After the assessment workshops, Monte Carlo simulations were run to estimate the metal abundances in undiscovered deposits for each tract. The tract reports were finalised and all assessment documents are combined in this report.

4.3 Data used

The assessment team used geological maps in digital and paper format, databases of mineral deposits and occurrences, technical reports on deposits and occurrences, mining company websites and published geological literature. The personal experience and knowledge of the assessment team members concerning many of the areas assessed was a valuable addition to the publicly available information. All data used in the assessment work for any permissive tract are listed in the respective tract description document in Appendix 3.

GTK report database (Hakku search service), published literature on known deposits, prospects and occurrences, and mining company websites were used as additional sources of information on Finnish deposits and occurrences.

4.3.3 Geophysical and geochemical data

The GTK in-house GIS map database of Finnish bedrock (Bedrock of Finland – DigiKP) formed the main source of lithological data for this work. The multi-scale database covers the whole of Finland and is regularly updated. A version of the database at the 1:200,000 scale can be viewed online at <http://gtkdata GTK.fi/mdae/index.html>. Detailed maps produced by exploration and research campaigns by various parties were also available for many areas assessed.

Low-altitude airborne magnetic survey data held by GTK (Hautaniemi et al. 2005), covering the whole of Finland, were used to support the delineation of permissive tracts. Gravimetric maps, based on data provided by the Finnish Geodetic Institute (Kääriäinen & Mäkinen 1997) or on regional gravity measurements by GTK where available (Elo 2003), were also occasionally utilised. Regional till geochemical data (Salminen 1995) and rock geochemical data (Rasilainen et al. 2007) were used in the delineation of permissive tracts. All the geophysical and geochemical data mentioned in this paragraph are available via the GTK website (Hakku search service).

4.3.4 Exploration history

The GTK mineral deposits, boulder observation and layman sample databases, the Mineral Deposits of the Fennoscandian Shield database (FODD 2018) and compilations of metallogenic belts in the Fennoscandian Shield (Eilu 2012) were the main sources of information for deposits and occurrences in Finland. These databases are available online via the Hakku search service on the GTK website (<https://hakku GTK.fi/en>). Where possible, the grade and tonnage data were checked and updated from company reports and publications. Reports in the

Spatial data on the location of effective and recently expired exploration permits and the coverage of geophysical measurements, geochemical sampling and diamond drilling by GTK, Outokumpu Oy and some other exploration companies, combined with information in exploration reports (Hakku search service), were used to estimate the coverage and intensity of exploration activities in various areas in Finland. This information was supplemented with further information from exploration and mining company websites, and with the personal knowledge of the assessment team members.

4.4 Deposit model

The grade-tonnage model for Kuusamo-type Co-Au deposits in Finland is described in Appendix 2. The model is based on 10 deposits within the Kuusamo area (Table 2 and Appendix 2). Statistical tests indicate that the distributions of ore tonnage, gold grade and cobalt grade do not significantly differ from lognormality. There are weak correlations between logarithmic ore tonnage and metal grade values, but Bonferroni-adjusted probabilities for the correlation coefficients indicate that these correlations are not significant (Appendix 2).

The grade-tonnage model is only based on 10 deposits, which suggests that it might not be representative of the true population of Kuusamo-type Co-Au deposits. Further, available information suggests that most of the deposits are open in some direction and that the reported resources do not represent the whole deposit. Because of these shortcomings, the grade-tonnage model used in the assessment probably gives a downward-biased representation of the true resources of Kuusamo-type Co-Au deposits.

Table 2. Summary statistics for the Kuusamo Co-Au grade tonnage model.

	Tonnage (Mt)	Co (%)	Au (g/t)
Number of deposits	10	10	10
Minimum	0.050	0.014	0.040
Maximum	7.429	0.23	7.2
Arithmetic Mean	1.624	0.11	2.4
Standard Deviation	2.463	0.072	2.2
10th percentile	0.090	0.022	0.20
50th percentile	0.503	0.089	2.0
90th percentile	6.054	0.22	5.6
Shapiro-Wilk p-value*	0.892	0.473	0.169

* Shapiro-Wilk normality test p-value was calculated for logarithmic tonnage and grade values. Tonnages are rounded to full thousands and grades to two significant digits.

4.5 Tract delineation

Permissive tracts were delineated for the Kuusamo-type Co-Au deposits based on the information described in section 4.3. For each area, the member or members of the assessment team most familiar with the geology and mineralisation of the region delineated the tracts. The criteria for the deline-

ation of each tract are given in the tract reports in Appendix 3. On a map, a permissive tract is a projection to the surface of the domain where geology allows the existence of the deposit type being assessed. The permissive volumes of rock were delineated down to a depth of one kilometre.

4.6 Estimation of the number of undiscovered deposits

The number of undiscovered deposits consistent with the Kuusamo-type Co-Au grade-tonnage model was estimated separately for each permissive tract in a series of workshops by the members of the assessment team. The experts considered the permissive volume of rock down to the assessment depth of one kilometre when making their estimates. No global deposit density model exists for Kuusamo-type Co-Au deposits, or for typical orogenic gold deposits. Hence, the estimates were based on the knowledge and experience of the experts, who considered all information, including indications of mineralisation, known occurrences and the extent of exploration in the tracts. Analogy with the rather well-known Kuusamo permissive tract was used as a guideline in estimating the

number of deposits in the other tracts. The existing grade-tonnage model was respected, to keep the estimates consistent with the known distribution of ore tonnages in Kuusamo-type Co-Au deposits. The spatial rule, according to which deposits less than 500 m apart are counted as one, was followed.

The names of the estimators for each permissive tract are given in the tract reports in Appendix 3. Each estimator independently assessed the number of undiscovered deposits at the 90%, 50% and 10% probability levels. The initial estimated numbers of undiscovered deposits were provided for discussion, during which the participants explained and sometimes adjusted their estimates. The purpose of the discussion was to determine whether a consensus estimate could be reached. When consensus was

not reached, the averages of the expert estimates at each probability level were used as the final estimates at the 90%, 50% and 10% probability levels.

According to the three-part method, incompletely known deposits and occurrences are considered as undiscovered. The estimator assesses the probability that an incompletely known deposit might, with further exploration, become a deposit with

potential for economically viable mining. However, the well-known deposits that are included in the grade-tonnage model are by definition assumed to be totally delineated and without any remaining unknown resources. This means that the possibly existing hidden resources in the well-known deposits were not considered and remained outside the assessment.

4.7 Assessment of metal tonnages

The assessment of metal tonnages in the undiscovered deposits was performed using Eminers software (Root et al. 1992, Duval 2012). As input, the software uses data from the grade-tonnage model and the estimated numbers of undiscovered deposits at the 90%, 50% and 10% probability levels. The software estimates an average non-parametric frequency distribution for the number of undiscovered deposits within a tract. It also estimates empirical and lognormal frequency distributions for the ore tonnage and metal grades in the grade-tonnage model. The software then runs Monte Carlo simulations using the estimated frequency distributions to produce estimates of ore and metal tonnages in the undiscovered deposits. For each simulation

round, metal tonnages are calculated by multiplying ore tonnage and metal grade values selected randomly from the constructed empirical or log-normal frequency distributions. As the final result of the simulation, the software produces probability distributions of the amount of metals and ore in the undiscovered deposits.

The assessment of metal tonnages in the undiscovered deposits was performed separately for each permissive tract. It is not statistically correct to add together the frequency distributions of ore and metal tonnages produced for the tracts. Hence, the total metal endowment for all undiscovered Kuusamo-type Co-Au deposits was estimated in a separate simulation run.

5 RESULTS AND DISCUSSION

The results of the Monte Carlo runs are simulated frequency distributions of ore and metal tonnages in the undiscovered deposits. These distributions combine the amount of undiscovered metal and the probability that this amount exists. The results of the Kuusamo-type Co-Au assessment are summarised in Tables 3–5 and Figures 8–10. Detailed assessment information for each permissive tract is presented in Appendix 3, where cumulative frequency distributions of undiscovered metal and ore tonnages are plotted and metal tonnages corresponding to several probability values are tabulated.

The arithmetic mean value of the frequency distribution for metal tonnage can be considered the expected amount of undiscovered metal. Since the frequency distributions of metal grades and ore tonnages in the Kuusamo-type Co-Au grade-tonnage model are skewed towards lognormal, the probabilities associated with the expected (mean) amounts

of undiscovered metal and ore are less than 50%; around 40% for aggregated results (Table 5) and generally 30–40% for individual permissive tracts (Appendix 3). On the other hand, there is a 50% probability that at least the amount of metal given by the median of the simulated frequency distribution (value associated with the 50th percentile) exists. This is why we prefer to report the median estimate of undiscovered metal and ore in Table 4, in which the results for individual permissive tracts are summarised. Table 5, which aggregates the total undiscovered lithium endowment over a number of permissive tracts, gives several percentile values to better characterise the frequency distributions of metal and ore tonnages. In the following, median estimates, i.e. values corresponding to the 50th percentile of the cumulative frequency distribution, are used when discussing the amounts of undiscovered metals.

5.1 Permissive tracts, number of deposits and metal endowment

In total, eight permissive tracts were delineated for Kuusamo-type Co-Au deposits (Fig. 8, Table 3, Appendix 3). These tracts contain all the known Kuusamo-type deposits and significant occurrences in Finland. Altogether, the tracts cover an area of 21,082 km², which is approxi-

mately 6% of the total land area of Finland. The size of the permissive tracts varies from 780 km² to 5611 km² (Table 3), and the median area is 2254 km². Maps of the individual permissive tracts are included in the tract reports in Appendix 3.

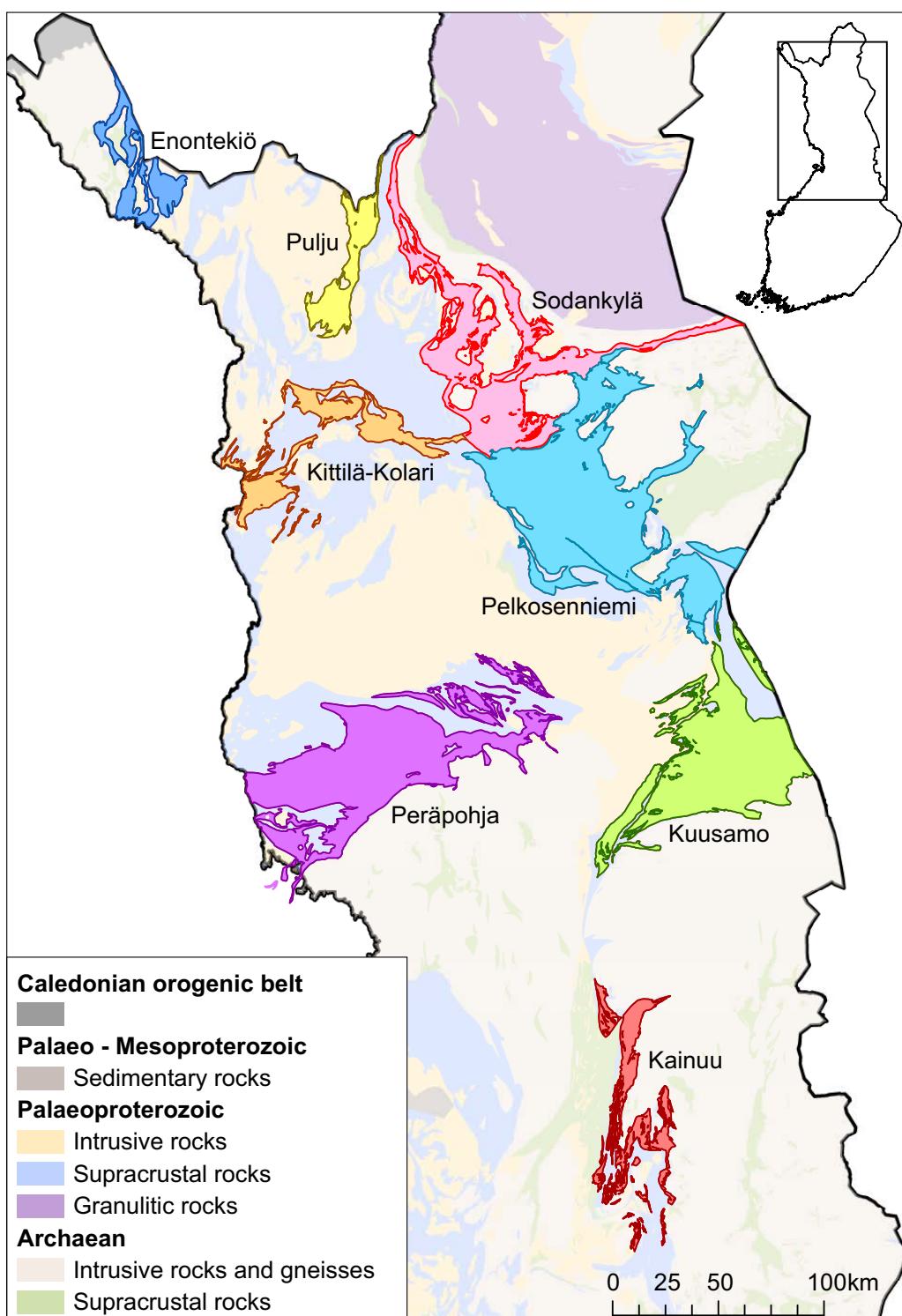


Fig. 8. Location of the Kuusamo-type Co-Au permissive tracts in Finland.

Table 3. Estimates for the number of undiscovered Kuusamo-type Co-Au deposit in the delineated permissive tracts in Finland.

Tract name	Estimated number of undiscovered deposits						Number of discovered deposits	Tract area (km²)	Total deposits	Deposit density (N/ km²)
	90th	50th	10th	E	Std	Cv				
Enontekiö Co-Au	1	4	10	4.8	3.3	68	0	780	4.8	0.0062
Kainuu Co-Au	1	5	15	6.7	5.1	76	0	1,076	6.7	0.0062
Kittilä-Kolari Co-Au	0	4	8	4.0	2.8	70	0	1,279	4.0	0.0031
Kuusamo Co-Au	6	11	29	14	8.7	60	10	3,684	24	0.0065
Pelkosenniemi Co-Au	2	8	18	9.1	5.7	63	0	5,611	9.1	0.0016
Peräpohja Co-Au	4	9	24	12	7.4	63	0	4,634	12	0.0026
Pulju Co-Au	0	2	5	2.3	1.8	80	0	790	2.3	0.0029
Sodankylä Co-Au	1	5	11	5.5	3.6	65	0	3,228	5.5	0.0017
Total over tracts			58.4				10	21,082	68.4	

90, 50, 10: Estimated number of undiscovered deposits associated with the 90th, 50th and 10th percentiles; E: Expected number (mean estimate) of undiscovered deposits; Std: Standard deviation; Cv: Coefficient of variation (%); N: Number of well-known deposits within the permissive tract; Total deposits: Sum of the number of well-known deposits and expected number of undiscovered deposits within the tract; Deposit density: Total number of deposits within the tract divided by tract area, rounded to two significant digits. E and Std are calculated using a regression equation (Singer & Menzie 2005).

The expected (mean) number of undiscovered Kuusamo-type Co-Au deposits for a permissive tract varies from two to nine deposits, and the sum of the mean estimates across all permissive tracts is 58 deposits (Table 4). Over 60% of the undiscovered deposits are estimated to be located within three permissive tracts: Kuusamo (24%), Peräpohja (21%) and Pelkosenniemi (16%).

The median estimate of the total *in situ* cobalt and gold endowment in undiscovered Kuusamo-type Co-Au deposits in Finland is at least 100,000 t of Co

and 85 t of Au (Table 5, Fig. 9). Approximately 50% of this is estimated to be located in undiscovered deposits in the Kuusamo and Peräpohja permissive tracts (Table 4, Fig. 10). As the identified resources in Kuusamo-type deposits are 21,700 t of Co and 19 t of Au, the assessment results indicate that at least 80% of the remaining Kuusamo-type cobalt and gold endowment within the uppermost one kilometre of the Finnish bedrock is in poorly explored or entirely unknown deposits.

Table 4. Summary of estimated undiscovered resources for Kuusamo-type Co-Au permissive tracts in Finland.

Tract name	Discovered resources (t)	Median undiscovered resources (t)	Mean undiscovered resources (t)
Enontekiö Co-Au	0	0	0
Kainuu Co-Au	0	0	11,000
Kittilä-Kolari Co-Au	0	0	5,400
Kuusamo Co-Au	21,698	19	16,243,000
Pelkosenniemi Co-Au	0	0	16,000
Peräpohja Co-Au	0	0	22,000
Pulju Co-Au	0	0	1,700
Sodankylä Co-Au	0	0	8,900
Total	21,698	19	16,243,000
			100,400
			84
			82,900,000
			136,500
			108

Ore: Mineralized rock containing the metals; Median undiscovered resources: The minimum amount of metals present within the permissive tract at the probability of 50%, rounded to two significant digits; Mean undiscovered resources: Arithmetic mean of the estimated amount of metals present within the permissive tract, rounded to two significant digits. Although it is not statistically strictly correct to sum the median estimates for individual tracts, the resulting totals are very close to the values obtained by including all the tracts in one simulation (Table 5).

Table 5. Summary of the identified and estimated undiscovered resources in Kuusamo-type Co-Au deposits in Finland.

Identified	At least the indicated amount at the probability of					Mean	Probability of		
	0.95	0.90	0.50	0.10	0.05		Mean or greater	None	
Co (t)	22,000	3,200	9,600	100,000	310,000	380,000	140,000	0.40	0.02
Au (t)	19	5.4	14	85	240	300	110	0.41	0.02
Ore (Mt)	16	3.4	10	83	220	260	100	0.42	0.02

Ore: Mineralised rock containing the metals. Well-known resources as of 29th May 2017. Data sources are listed in Appendix 2.
All resources are rounded to two significant digits.

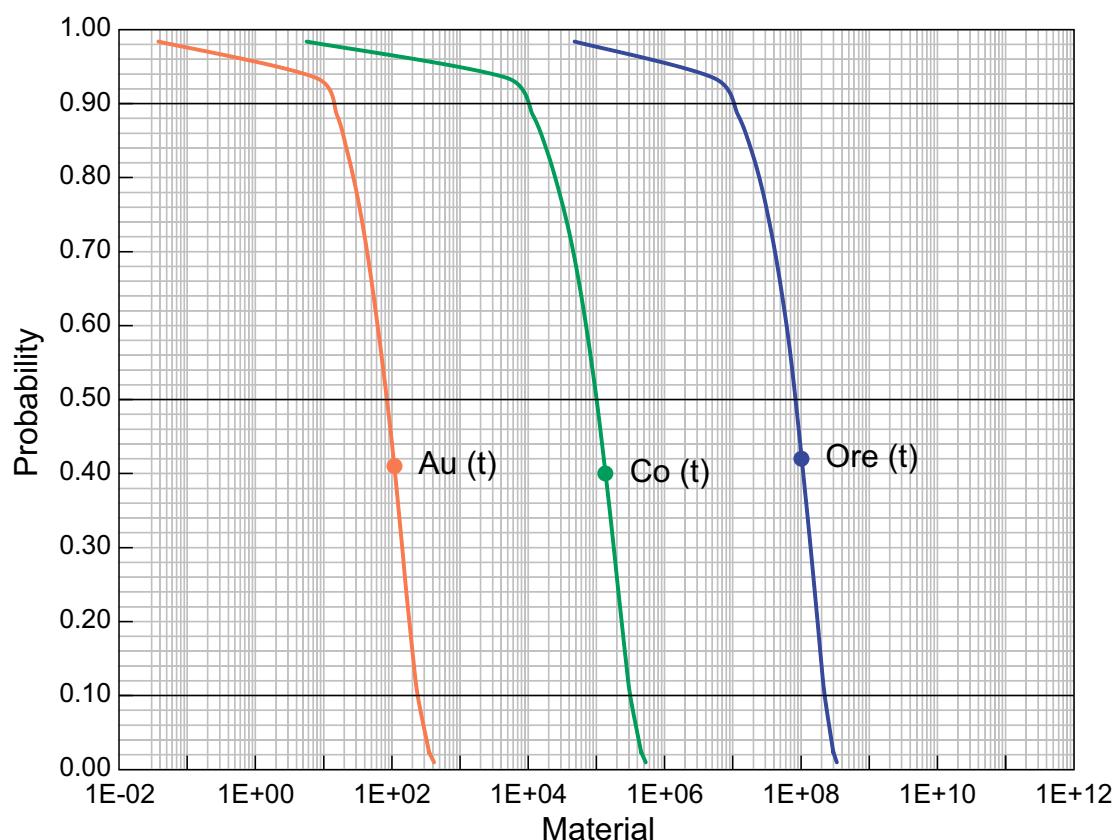


Fig. 9. Cumulative frequency distributions of simulated undiscovered resources in Kuusamo-type Co-Au deposits in Finland.

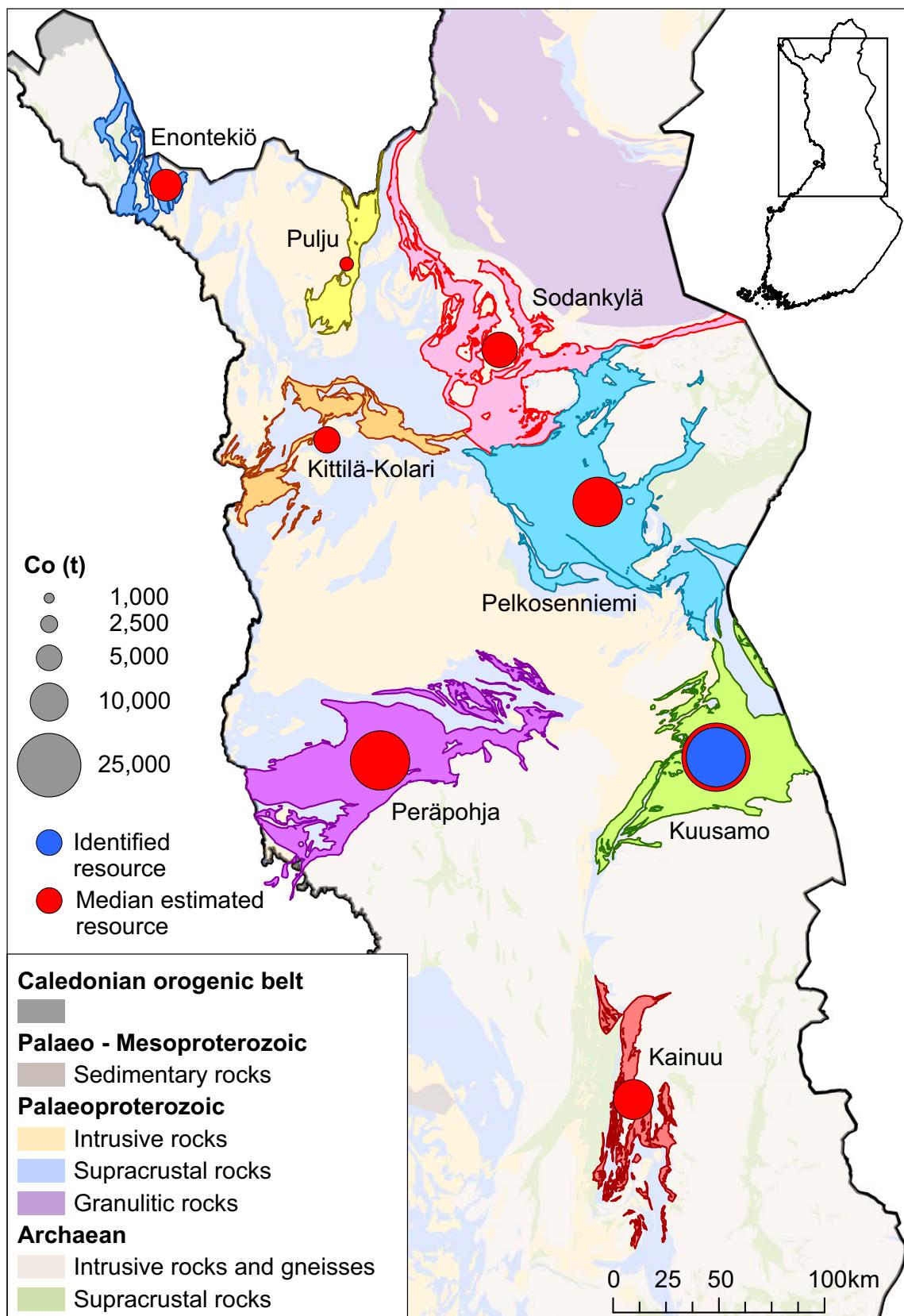


Fig. 10. Estimated undiscovered Kuusamo-type Co-Au resources in Finland plotted on each permissive tract.

5.2 Kuusamo-type versus total cobalt endowment in Finland and globally

The known endowment of cobalt in various types of deposits in the Finnish bedrock is approximately 430,000 t of Co (FODD 2018). Of this amount, 85% is in four deposits: Talvivaara, Kevitsa, Sakatti and Kylylahti (Table 1). The median undiscovered endowment of 100,000 t of Co estimated to be in Kuusamo-type deposits is approximately 20% of the total known endowment.

Undiscovered cobalt resources in Finland have previously been assessed for synorogenic intrusion-related Ni-Cu deposits, komatiite-related Ni-Cu-PGE deposits and Outokumpu-type Cu-Co-Zn deposits in Finland (Table 6). According to the results of the present study, approximately half of the undiscovered cobalt endowment yet estimated in Finland is in Kuusamo-type Co-Au deposits. On the other hand, it has not been possible to estimate the undiscovered cobalt resources in Talvivaara-type Ni-Zn-Cu-Co deposits or Kevitsa-type Ni-Cu-PGE deposits. The results of the present and previous assessments indicate that: (1) undiscovered Kuusamo-type cobalt endowment forms less than half, but still a significant part, of the total undiscovered cobalt endowment in Finland; and (2) the total undiscovered cobalt endowment can be expected to form at least 20–40% of the total cobalt endowment in the Finnish bedrock.

Identified world terrestrial cobalt resources are about 25 Mt, and more than 120 Mt of cobalt resources have been identified in manganese nodules and crusts on the ocean floor (U.S. Geological Survey 2019). Compared with these figures, the Finnish endowment is insignificant. The known cobalt resources in Finland are about 2%, and the estimated total cobalt endowment in Finland is likely to be less than 3%, of the identified world terrestrial resources.

In a European context, the Finnish cobalt resources are significant. According to the database of S&P Global Market Intelligence (2019), the known European cobalt resources outside of Finland are 93,000 t. Most of these (80%) are in Russia, Albania and Turkey, and the rest are divided between Serbia, Spain, Norway and Sweden. On the other hand, Lauri et al. (2018) report cobalt resources of at least 239,000 t in Europe, outside of Finland. Almost 90% of these are located in Greece and Poland, and the rest are in Sweden, Norway and Spain. These European-wide estimates indicate that the Finnish identified resources form 65–88% the known cobalt resources in Europe.

Table 6. Comparison of Kuusamo-type and other undiscovered cobalt resources in Finland.

Deposit type	Co (t)		
	Identified	Median undiscovered	Mean undiscovered
Kuusamo-type Co-Au	22,000	100,000	140,000
Synorogenic intrusion-related Cu-Ni	9,300	23,000	44,000
Komatiite-related Cu-Ni-PGE	1,700	10,000	18,000
Outokumpu-type Cu-Co-Zn	26,000	53,000	68,000
Total	59,000	186,000	270,000

Resources for each deposit type are rounded to two significant digits.

Data sources for other than Kuusamo-type deposits: Rasilainen et al. (2012, 2014), FODD (2018). Resources for the individual deposit types have been rounded to two significant digits.

5.3 Reliability and usability of the estimates

Considering the reliability of the assessment results, sensitivity analysis indicates that changes in grade and tonnage estimates have a much larger influence on the expected metal content in an assessment than changes in the expected number of deposits

(Singer & Kouda 1999). Consequently, the greatest sources of possible error in the present assessments are associated with the grade-tonnage models used.

As deposits strictly similar to the Kuusamo Co-Au deposits are not known elsewhere, the grade-ton-

nage model used in the assessment was based on 10 deposits within the Kuusamo area. This can be considered to take the local geological characteristics of Kuusamo-type deposits better into account than a global model, which might contain larger variation in deposit characteristics, ore tonnages and metal grades. On the other hand, the small number of deposits causes uncertainty in the grade-tonnage model and its representativeness of the true population of Kuusamo Co-Au deposits.

It is of the utmost importance that the grade and tonnage information included in the grade-tonnage model represents as accurately as possible total deposits of the correct deposit type. However, even deposits that are considered to be well known may contain undiscovered resources. This is certainly the case with the known Kuusamo-type Co-Au deposits; it is likely that most of the deposits in the grade-tonnage model (Appendix 2) are not entirely delineated. This suggests that the grade-tonnage model underestimates the metal contents of the Kuusamo-type Co-Au deposits. Consequently, the amounts of cobalt and gold in the undiscovered resources estimated based on the grade-tonnage model might be smaller than the true metal contents in the undiscovered deposits. On the other hand, the size distribution of the undiscovered deposits was taken into account by the experts when

estimating the number of undiscovered deposits within the permissive tracts.

Finally, care must always be taken when applying the results of assessments such as these. Although the assessment method predicts the existence of a number of undiscovered deposits, it gives no guarantee that these deposits will ever be discovered. Many of the undiscovered deposits estimated to exist in the present work can be under hundreds of metres of barren rock, whereas others may crop out at the surface. Some of the buried deposits are likely to be beyond the reach of present day exploration technology, or their discovery may require exploration expenditures so large they are unlikely to be discovered in the near future. As the grade-tonnage models used in three-part assessments typically contain uneconomic occurrences in addition to operating mines, the resulting estimated undiscovered resources are also partly located in uneconomic occurrences. Although technological advances act over time to lower mining costs and allow formerly uneconomic occurrences to become operating mines, some of the undiscovered deposits estimated here might never be mined for one or more reasons, including relatively low tonnages or grades, deep burial, or occurrence in or near environmentally sensitive areas or areas designated for other land uses than mining.

6 SUMMARY

Experts in mineral deposits, metallogeny and geo-statistics at the Geological Survey of Finland produced this assessment of undiscovered cobalt and gold resources in Kuusamo-type Co-Au deposits within the uppermost one kilometre of the Finnish bedrock. The resources were assessed using the three-part quantitative method developed at the U.S. Geological Survey. This report provides numerical estimates of the expected endowment of cobalt and gold in undiscovered, potentially exploitable Kuusamo-type Co-Au deposits.

The main results are that:

1. The three-part quantitative assessment method is suitable for assessing Kuusamo-type Co-Au deposits.
2. The number of well-known Kuusamo-type Co-Au deposits in Finland is 10, and all of these

are located in the Kuusamo area. The identified resources in these deposits are 21,698 t of cobalt and 19 t of gold.

3. A local grade-tonnage model was constructed using information on the 10 well-known Kuusamo-type Co-Au deposits in Finland. Most of the deposits in the grade-tonnage model are probably not totally delineated.
4. Eight permissive tracts were delineated for Kuusamo-type Co-Au deposits in Finland. The tracts cover 21,082 km², which is approximately 6% of the total land area of Finland.
5. The expected number of undiscovered Kuusamo-type Co-Au deposits in Finland is 58.
6. The undiscovered Kuusamo-type Co-Au deposits are estimated to contain, at 50% probability, at least 100,000 t of cobalt and 85 t of gold.

7. Approximately 50% of the estimated undiscovered Kuusamo-type cobalt resources are located within the Kuusamo and Peräpohja permissive tracts.
 8. The assessment results indicate that at least 80% of the remaining Kuusamo-type cobalt endowment within the uppermost one kilometre of the Finnish bedrock is in poorly explored or entirely unknown deposits.
 9. The results of this and previous assessments indicate that at least 20–40% of the total cobalt endowment within the uppermost one kilometre of the Finnish bedrock is in poorly explored or entirely unknown deposits.
10. The known cobalt resources in Finland constitute approximately 2%, and the estimated total cobalt endowment in Finland is likely to be less than 3%, of the identified world terrestrial resources.
11. Within a European context, the known and estimated undiscovered cobalt endowment is significant.

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APPENDIX 1

DESCRIPTIVE MODEL FOR KUUSAMO-TYPE Co-Au DEPOSITS

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APPROXIMATE SYNONYMS

None

DESCRIPTION

Structurally controlled Co-Cu-Au deposits in a Palaeoproterozoic supracrustal sequence in a rifted basin with extensive, early albitisation, multistage proximal alteration and indications of evaporates, apparently hosted only by rocks not younger than 2.20 Ga. These are only known from the Kuusamo schist belt. In geological setting and parts of the style of alteration and probable timing, the Saattopora (Central Lapland greenstone belt), Rajapalot (Peräpohja belt) and Bidjovagge (Kautokeino greenstone belt, Norway) deposits are similar to the Kuusamo deposits (Eilu 2015, Ranta

et al. 2018). Globally, somewhat similar deposits are suggested to exist at Blackbird (Idaho Cobalt Belt, USA), Modum (Norway), Cobalt Hill (Canada), Mt Cobalt (Australia) and Kendekeke and Dahenglu (China) (Slack et al. 2010, Slack 2013). However, we do not see sufficient similarity with Saattopora and Bidjovagge, or with the metasedimentary-hosted Co-Cu-Au deposits, to include these in this descriptive model. Hence, we do not use the USGS-defined ‘Metasedimentary-hosted Co-Cu-Au deposits’ (Slack et al. 2010, Slack 2013) as a synonym for the Kuusamo-type deposits.

DEPOSIT EXAMPLES

Hangaslampi
Juomasuo
Meurastuksenaho

Vanhainen (2001)
Vanhainen (2001)
Vanhainen (2001)

GEOLOGICAL ENVIRONMENT

Host rocks

Clastic sedimentary and basaltic extrusive rocks of a rift-shelf sequence in an intracratonic (or possibly epicratonic) rift, in the Karelian domain, only

known in ca. 2.35–2.20 Ga rocks (Erkki Vanhanen, pers. comm. 2010). Dominant host rocks at Kuusamo are albitised metasiltstone and sericite quartzite.

Age

Gangue mineral assemblages suggest sulphidic mineralisation being post-peak metamorphic (Korteniemi 1993, Vanhanen 2001). Monazite ages

from the Hangaslampi deposit suggest mineralisation during 1850–1810 Ma (Pohjolainen et al. 2017).

Mineralisation environment

Clastic sedimentary sequence also including evaporates and basaltic to komatiitic volcanic rocks. Extensive and intense sodic ± CO₂ (albite ± carbonate) and Na-Cl (scapolite) alteration predating the orogeny and mineralisation. Syn-orogenic, structurally-controlled mineralising fluids. No causative intrusion has been identified, although Al-Ani et al. (2018) suggest carbonatitic magma-

tism having had some effect at one of the Kuusamo occurrences. Metal association requires medium- to high-salinity fluid at least for some of the hydrothermal stages. The higher than normal fluid salinity in a metamorphic environment can be explained by the evaporate-derived diagenetic fluids at least partly remaining in the sequence into an orogeny (Yardley & Graham 2002).

Tectonic setting

Intracratonic failed rift setting containing clastic sediments, evaporates ± mafic-ultramafic volcanic and subvolcanic rocks. Unclear if an epicratonic

setting could also be possible; there are no clear indications of that within the Kuusamo belt. Deep-water supracrustal environment is excluded.

Associated deposit types

Barren epigenetic pyrrhotite-pyrite and minor epigenetic selenide occurrences in the region. Evaporate beds, totally replaced and partly destroyed during diagenesis and regional metamorphism. Genetic relationship to IOCG deposits has been suggested (Vanhansen 2001, Slack 2013), but no clear IOCG deposits have been detected within the Kuusamo belt. In the Peräpohja belt, there is one IOCG deposit and a set of epigenetic Au-Cu, Au-Co, Au-U and

Au-only deposits and occurrences, which may all not belong to the orogenic gold category. In the Kolari area, there are distinct IOCG deposits, on the other hand. In Central Lapland, there are both gold-only and gold-copper orogenic gold deposits, including occurrences whose timing may be similar to the Kuusamo Au-Co deposits, and some of which also are hosted by pre-gold, extensively albitised supracrustal rocks.

DEPOSIT DESCRIPTION

Ore minerals

Native gold, pyrite, pyrrhotite, cobaltite, cobaltian pentlandite, pentlandite, chalcopyrite, uraninite, bismuth and tellurium minerals (e.g. calaverite, clauthalite, frohbergite, kawazulite, melonite,

rucklidgeite, tellurobismuthite), rutile, in some cases also selenides, molybdenite, magnetite, ilmenite, bornite, covellite, linnaeite.

Texture and structure

Syn-sedimentary structures, including layering, dissolution features and possible fluid escape channels are preserved, as is albite-rich layering containing ferrodolomite displaying relict crystal shapes possibly representing pseudomorphs after evaporate minerals (e.g. gypsum, halite). Localised hydrothermal-looking breccias with variable metal

grades and intense carbonate-albite alteration (e.g. at Konttiaho). Native gold may occur associated with bismuth and tellurium minerals as inclusions in pyrite, cobaltite and uraninite, between silicates, and in tiny Au-Bi-Te veinlets. Also free native gold associated with major sulphides and gangue.

Ore control

The deposits in the Kuusamo belt occur at locations where faults intersect with regional anticlines. Juomasuo and its satellite deposits are in a doubly plunging site of an antiform. The known ore bodies are within extensive albitised domains (prepared

ground?), at locations with several localised stages for post-albitisation alteration. The localised alteration includes sericitisation, chloritisation, carbonation + albitisation, and biotitisation, which are all, at least spatially, directly related to mineralisation.

Weathering products

Placer gold and gossan occurrences are possible, but have not been detected.

Geochemical signature

Metal association is Au-Co. Enriched elements include As-Au-Ba-Bi-Co-Cu-K-LREE-Mo-Rb-S-Se-U-Te-W ± CO₂, Fe, HREE, Mn, Mo, Ni, Pb, Th. Au/Ag >1. The deposits are always hosted or at least enveloped by albitised and carbonated rocks, but there is commonly a loss of sodium and calcium in the ore itself. The latter chemical changes are related to the localised, syn-orogenic, stages of

alteration and mineralisation. Distinct metal zoning has been detected in two Kuusamo deposits: Au-Co ore enveloped by cobalt ore. Regional Na, Na-Cl and CO₂ enrichment is reflected by albitisation, carbonatisation and scapolitisation, respectively. Scapolitisation has not been detected in the mineralised bodies or in their immediate country rocks.

Geophysical signature

All currently known Kuusamo deposits have been discovered by radiometric survey. However, if uranium or thorium is not enriched, the radiometric method may not indicate the Kuusamo-type

Au-Co deposits. Magnetic survey can be used to map controlling structures. Electromagnetic survey, especially IP, potentially indicates the sulphidised domains, i.e. the potential ore.

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APPENDIX 2

GRADE-TONNAGE MODEL FOR KUUSAMO-TYPE Co-Au

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INTRODUCTION

The grade-tonnage model described here contains data from 10 cobalt-gold deposits in the Kuusamo area, Finland. A spatial rule was applied, according to which deposits less than 500 m from each other were combined. Kuusamo-type Au-Co deposits with a published resource estimate are only known from the Kuusamo area. Due to the small number of well-known deposits, historical resource estimates were accepted in the grade-tonnage model, in addition to estimates according to modern standards.

According to the three-part assessment method, the resource estimates should cover well-explored

and totally delineated deposits. However, in the case of available data for Kuusamo-type deposits, this is almost never the case, but most of the deposits are reported to be open to at least some direction. This means that the tonnage model based on the available resource data represents partial deposits, and that estimates of undiscovered Kuusamo-type Co-Au resource tonnage based on this model are conservative.

DATA

Kuusamo-type structurally controlled Co-Au deposits are only known from the Kuusamo schist belt in Finland. Hence, the grade-tonnage model presented here is based on available data for well-known deposits within the Kuusamo belt.

The mineral deposits database of the Geological Survey of Finland, the mineral deposits of the Fennoscandian Shield database (FODD) and compilations of metallogenic belts in the Fennoscandian Shield (Eilu 2012) were used to search for information on known Kuusamo-type Co-Au deposits and occurrences in Finland. These databases are available online via the Hakku search service on the GTK

website (<https://hakku GTK.fi/en>). The grade and tonnage data for these deposits were verified and, when possible, updated from company reports and publications.

Data from the above-mentioned sources were compiled into a dataset, which was used to construct the final grade-tonnage model for the Kuusamo-type Co-Au deposits. The initial dataset contained 11 deposits, but one of these, Iso-Rehvi (Vanhainen 1990, 1991, Strauss 2006) was excluded due to too few and uncertain data for a reliable resource estimate.

STATISTICS

The final dataset is listed in Table 1. Since copper grade information was available for only three of the 10 deposits in the dataset, copper was not included in the statistical analysis of the data. Statistical tests indicate that the distributions of ore tonnage, gold grade and cobalt grade do not significantly differ

from lognormality (Table 2, Fig. 1). There are weak correlations between logarithmic ore tonnage and metal grade values, but Bonferroni-adjusted probabilities for the correlation coefficients indicate that the correlations are not significant (Fig. 2, Table 3).

Table 1. Deposits used to construct the Kuusamo-type Co-Au grade-tonnage model.

Deposit	Resource date	Reporting standard	Cut-off	Tonnage (Mt)	Au (g/t)	Co (%)	Cu (%)	Reference
Apajalahti	May 1980	Old	0.1 g/t Au	0,1293	4,04	0,01 ^a	0,05	Lahtinen (1980)
Haarakumpu	April 1984	Old	0.1% Co or 1.0% Cu	4,68	0,04 ^b	0,17	0,34	Vartiainen (1984)
Hangaslampi total ^c	June 2012	JORC (2004)	0.5 g/t Au or (1.0% S and 0.01% Co)	0,583	3,6	0,07	-	Dragon Mining (2012)
Juomasuo total ^d	March 2014	JORC (2004, 2012)	1 g/t Au or 0.05% Co	7,428635	1,6	0,12	-	Dragon Mining (2013, 2014), Puustinen (2003)
Kouvelvaara	September 1988	Old	0.05% Co	1,554	0,38	0,089	-	Vanhanen (1988)
Lemmonlampi	March 1987	Old	n.a.	0,37	0,35	0,23	0,52	Korkalo (1987)
Meurastuk-senaho	March 2014	JORC (2012)	1 g/t Au, 0.05% Co	0,892	2,3	0,2	-	Dragon Mining (2014)
Pohjasvaara	March 2014	JORC (2012)	1 g/t Au, 0.05% Co	0,133	3,8	0,09	-	Dragon Mining (2014)
Säynäjävaara	August 1985	Old	none	0,423	1,1	0,06	-	Tarvainen (1985)
Sivakkaharju	March 2014	JORC (2012)	1 g/t Au, 0.05% Co	0,05	7,2	0,03	-	Dragon Mining (2014)

^a: Co for Apajalahti is based on regression on Au in drill core samples having Au>0.1 g/t

^b: Au for Haarakumpu is based on regression on Co and Cu in drill core samples having Co>0.1% or Cu>1%.

^{c,d}: Combined resource containing both Au- and Co-dominated ore bodies.

-: Data not available

Table 2. Summary statistics for the Kuusamo Co-Au grade tonnage model.

	Tonnage (Mt)	Co (%)	Au (g/t)
Number of deposits	10	10	10
Minimum	0.050	0,014	0.040
Maximum	7.429	0,23	7,2
Arithmetic Mean	1.624	0.11	2.4
Standard Deviation	2.463	0,072	2.2
10th percentile	0.090	0,022	0.20
50th percentile	0.503	0,089	2.0
90th percentile	6.054	0.22	5.6
Shapiro-Wilk p-value*	0,892	0,473	0,169

* Shapiro-Wilk normality test p-value was calculated for logarithmic tonnage and grade values. Tonnages are rounded to full thousands and grades to two significant digits.

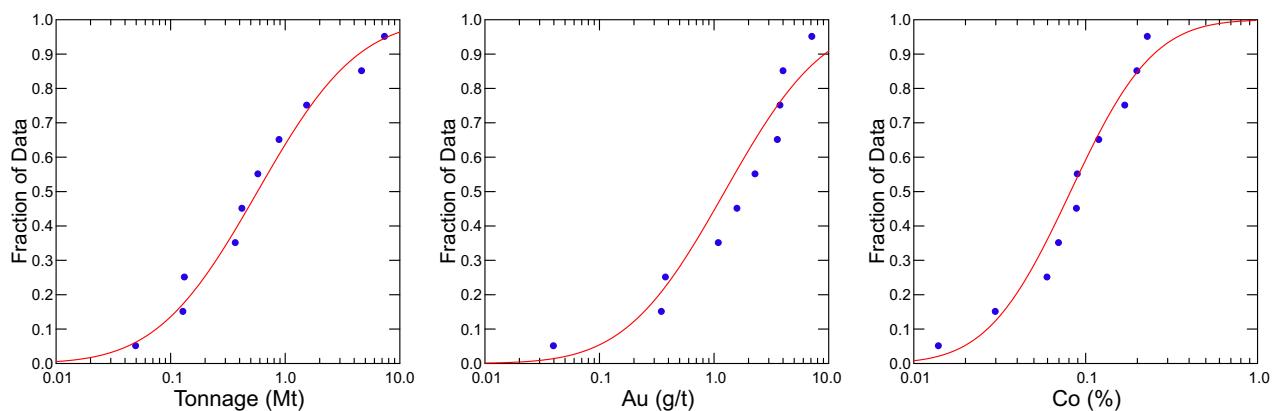


Fig. 1. Cumulative frequency plots of ore tonnage and metal grades for the deposits in the Kuusamo Co-Au dataset. The estimated lognormal cumulative distribution functions are shown as solid lines.

Table 3. Correlation coefficients and corresponding probabilities for the Kuusamo Co-Au deposits.

Pearson correlation coefficients

	Log(Tonnage)	Log(Au)	Log(Co)
Log(Tonnage)	1		
Log(Au)	-0,648	1	
Log(Co)	0,608	-0,582	1

Bonferroni probabilities

	Log(Tonnage)	Log(Au)	Log(Co)
Log(Tonnage)	0		
Log(Au)	0,128	0	
Log(Co)	0,186	0,233	0

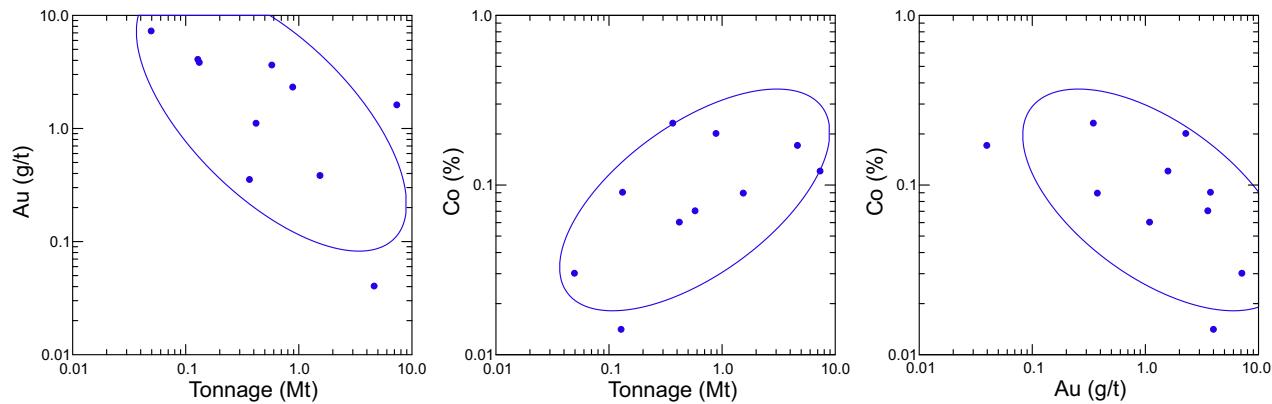


Fig. 2. Relationship between ore tonnage and metal grades for the deposits in the Kuusamo Co-Au dataset. The confidence ellipsoids are centred on the data means of x and y variables. One unbiased sample standard deviation of x and y determines their major axes, and the sample covariance between x and y their orientation.

THE GRADE-TONNAGE MODEL

The grade-tonnage model for Kuusamo Co-Au deposits was constructed based on the 10 well-known deposits in the dataset. Due to the severely restricted information on copper grades in the dataset, copper was not included in the grade-tonnage model. Summary statistics of the model are given in Table 2.

The grades and tonnages in a grade-tonnage model should represent the total deposit, including past production. However, in the case of Kuusamo-type Co-Au deposits, this criterion is difficult to

fulfil. Most of the 10 deposits in the grade-tonnage model are obviously open to depth, along strike, or both, and the reported resources consequently represent only parts of the deposits. This, in combination with the small number of deposits, makes the model unstable and most likely unrepresentative of the true population of Kuusamo Co-Au deposits. More data on totally delineated deposits is needed for the construction of a representative grade-tonnage model for Kuusamo Co-Au deposits.

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APPENDIX 3

ASSESSMENT RESULTS FOR THE KUUSAMO Co-Au PERMISSIVE TRACTS

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Co ASSESSMENT FOR THE TRACT ENONTEKIÖ Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Enontekiö Co-Au permissive tract is located in north-western Lapland, Finland, and occupies the central part of the municipality of Enontekiö (Fig. 1). The 1:50,000 UTM map sheets are W334, W333, V344, W411, V422 and V421. The Co-Au resource assessment carried out for this report is summarised in Table 1.

1). The 1:50,000 UTM map sheets are W334, W333,

Table 1. Summary of selected resource assessment results for the Enontekiö Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
14/08/2018	1	780	Co	0	Co
			Au	0	Au

t – metric ton

DELINeATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of Palaeoproterozoic supracrustal rocks belonging to the Lätäseno Group and the Hietakero and Salvastunturi lithodemes. These rocks are characterised by strong scapolitisation and albitisation, locally also by carbonatisation, similar to their

counterparts in the Kuusamo area. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-known Kuusamo-type Co-Au deposits within the Enontekiö Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Enontekiö Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Content of metal (t)	Reference
<hr/>							

Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No obvious Kuusamo-type Co-Au occurrences are known within the tract (Table 3). Within the tract area, there is the mafic intrusion-hosted Hietakero Co-Cu-Ni occurrence, with reported drill core intersections containing 5 m @ 0.1% Co, 0.2% Ni and

0.35% Cu, and 14 m @ 0.1% Co, 0.23% Ni and 0.31% Cu (Karinen et al. 2018). Also in the tract area is the Vähäkurkkio copper showing (cobalt not analysed) and some Co-Cu enriched albitite boulders have been found along the river Lätäseno.

Table 3. Significant Kuusamo-type Co-Au occurrences and related deposit types in the Enontekiö Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
<hr/>					

Ma – million years

Exploration history

Exploration activities for the Kuusamo Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Enontekiö Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Geochemical surveys	Bedrock mapping	Yes	GTK	1981–1983
	Bedrock mapping	Yes	GTK	2008–2016
	Outcrop observations and boulder survey	Yes	Outokumpu Oy	1950s–1980s
	Targeting and sub-regional geochemical surveys	Yes	Outokumpu Oy, Rautaruukki Oy	1960s–1980s
	Pohjoiskalotti geochemical survey (till, stream sediments, humus, water)	Yes	GTK	1980
	Nationwide till survey (1 sample/4 km ²)	Yes	GTK	1980s–1990s
	Targeting geochemical till sampling	Yes	GTK	1970s–1980s
	Targeting geochemical stream sediment sampling	Yes	GTK	1970s–1980s
	Lätäseno and Hietakero targeting geochemical till sampling	Yes	GTK	2011–2012
	Targeting till geochemical and quaternary survey	Yes	GTK	2011
Airborne geophysical surveys	Lätäseno targeting stream sediment sampling	Yes	GTK	2013
	Lätäseno targeting biogeochemical survey	Yes	GTK	2013
	Nationwide high-resolution low-altitude airborne magnetic, EM and radiometric surveys		GTK	1983–2002
Ground geophysical surveys	Tsohkoavi–Lätäseno and Hietakero time-domain electromagnetic airborne survey (SkyTEM)		GTK	2012
	Systematic gravimetric survey, 1085 km ² (4 p/km ²)		GTK	1980s, 2011–2016
	Vähäkurkkio systematic magnetic and slingram survey		Outokumpu Oy	1972–1973
	Sinettä systematic magnetic, slingram and gravimetric survey		GTK	1979
	Kelottijärvi, Markkina and Nunastunturi systematic magnetic and slingram survey		GTK	1982–1983
	Targeting profile magnetic, gravimetric, IP and VLF-R survey		GTK	2009–2012
	Hietakero systematic magnetic survey		GTK	2017
Drilling	Lätäseno diamond drilling, 3 DDH, 394 m	Yes	Outokumpu Oy	1975
	Vikkuri diamond drilling, 3 DDH, 450 m	Yes	GTK	1986
	Vuontisjärvi–Sinettä diamond drilling, 6 DDH, 94 m	No	Outokumpu Oy	1995
	Kalkkoavi diamond drilling, 8 DDH, 826 m	Yes	GTK	2010
	Kennovaara diamond drilling 1 DDH, 100 m	No	GTK	2010
	Lätäseno diamond drilling, 20 DDH, 2590 m	Yes	GTK	2011–2012
	Hietakero diamond drilling, 13 DDH, 1672 m	Yes	GTK	2012
	Rissiselkä diamond drilling, 2 DDH	Yes	GTK	2014
	Hietakero diamond drilling, 9 DDH, 1701 m	Yes	GTK	2016

DDH – diamond drill hole; GTK – Geological Survey of Finland

Generalized Lithology 1M**Palaeoproterozoic**

- Granite
- Paraschist
- Volcanic rocks, dominantly mafic in composition
- Quartzite
- Layered mafic intrusions

Archaean

- Paraschist and -gneiss
- Volcanic rocks, dominantly mafic composition
- TTG gneiss and migmatite

Co-Au tract

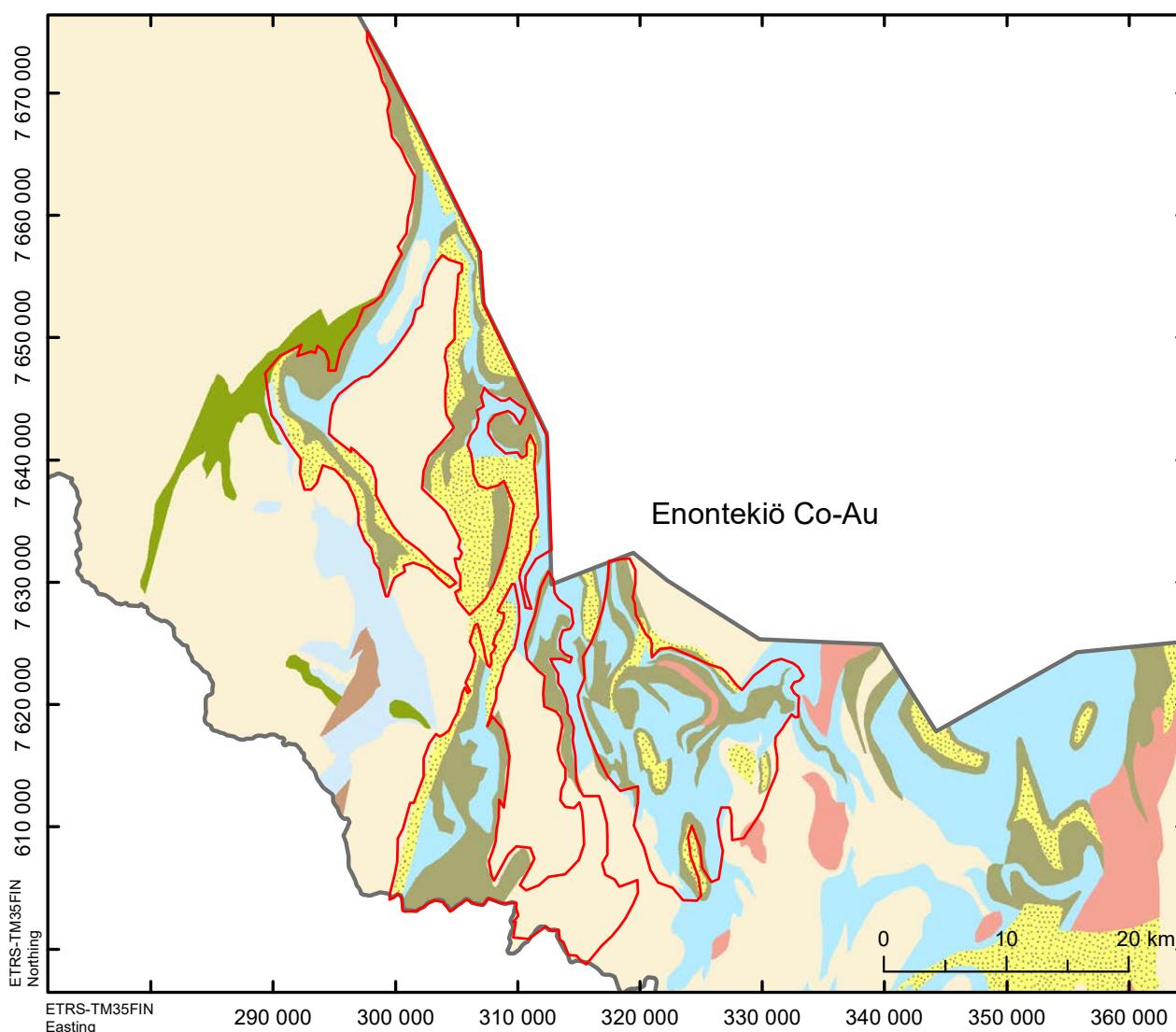
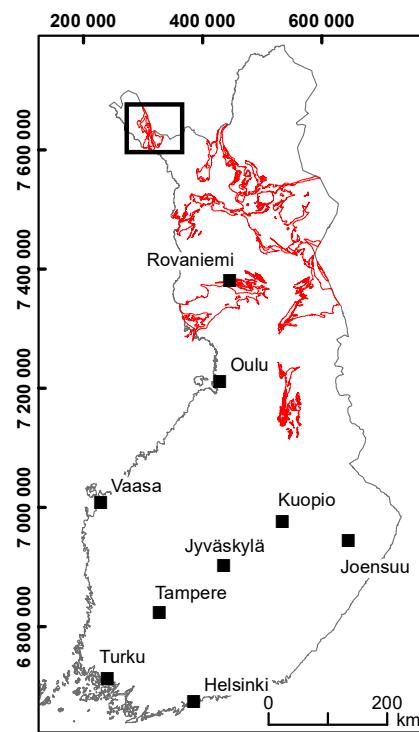


Fig. 1. Location of the Enontekiö Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Enontekiö Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Enontekiö Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP, http://gtkdata GTK.fi/Kalliopera/index.html
	Reports and publications		Inkinen (1975), Lahtinen (1977), Eilu (1984), Eilu & Idman (1988), Bergman et al. (2001), Karinen et al. (2015, 2018), Konnunaho et al. (2013, 2018), Hulkki et al. (2018)
Mineral occurrences and exploration	Mineral deposit and exploration database		http://gtkdata GTK.fi/mdae
	Reports and publications		Inkinen (1975), Reino (1975), Lahtinen (1977), Lehtinen & Eilu (1987), Konnunaho et al. (2013, 2018), Karinen et al. (2015, 2018), Hulkki et al. (2018)
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search
Geochemistry	National drill core archive, Loppi		https://www GTK.fi/en/research-infrastructure/national-drill-core-archive/
	GTK online and in-house databases		https://hakku GTK.fi/en/locations/search
	Reports and publications		Wennervirta (1963), Inkinen (1975), Sarala et al. (2011), Konnunaho et al. (2013, 2018), Hulkki et al. (2018)
Geophysics	GTK online and in-house databases		http://gtkdata GTK.fi/MdaE , https://hakku GTK.fi/en/locations/search
	Report and publications		Inkinen (1975), Isomaa (1991), Airo (1999), Bergman et al. (2001), Konnunaho et al. (2013), Sarala et al. (2015), Karinen et al. (2018)

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

Kuusamo-type Co-Au deposits or occurrences have not been detected within the tract area. However, one Co-enriched Cu-Ni deposit has been discovered by GTK, which indicates Co-enriching hydrothermal processes have been active in the area. The tract covers Palaeoproterozoic supracrustal rocks of the Enontekiö area, and these rocks are highly scapolitised, albited and locally carbonated in a similar fashion as the supracrustal rocks in the Kuusamo area and in other parts of

Palaeoproterozoic supracrustal belts in northern Fennoscandian shield. Exploration activities in the Enetekiö tract have mostly focused on Ni-Cu-PGE-potential mafic and ultramafic magmatic units, whereas the highly altered supracrustal sequences have remained poorly explored. No consensus on the number of undiscovered deposits was reached in the discussions, and the mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Enontekiö Co-Au permissive tract.

Mean undiscovered deposit estimate					Summary statistics				Area (km ²)	Deposit density (N/km ²)	
N90	N50	N10	N05	N01	N _{und}	s	Cv%	N _{known}	N _{total}		
1	4	10			4.8	3.3	68	0	4.8	780	0.0062

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	0	3	6		
Individual 2	1	6	18		
Individual 3	2	6	10		
Individual 4	0	2	8		
Individual 5	1	4	8		
Individual 6	1	4	10		
Individual 7	1	4	12		
Mean	1	4	10		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Juhani Ojala, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and the total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Kuusamo Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	0	140	7,400	28,000	35,000	11,000	0.39	0.07
Au (t)	0	0.47	6.5	21	28	9.0	0.39	0.07
Rock (Mt)	0	0.20	7.1	19	24	8.5	0.43	0.07

Mt – million metric tons; t – metric ton

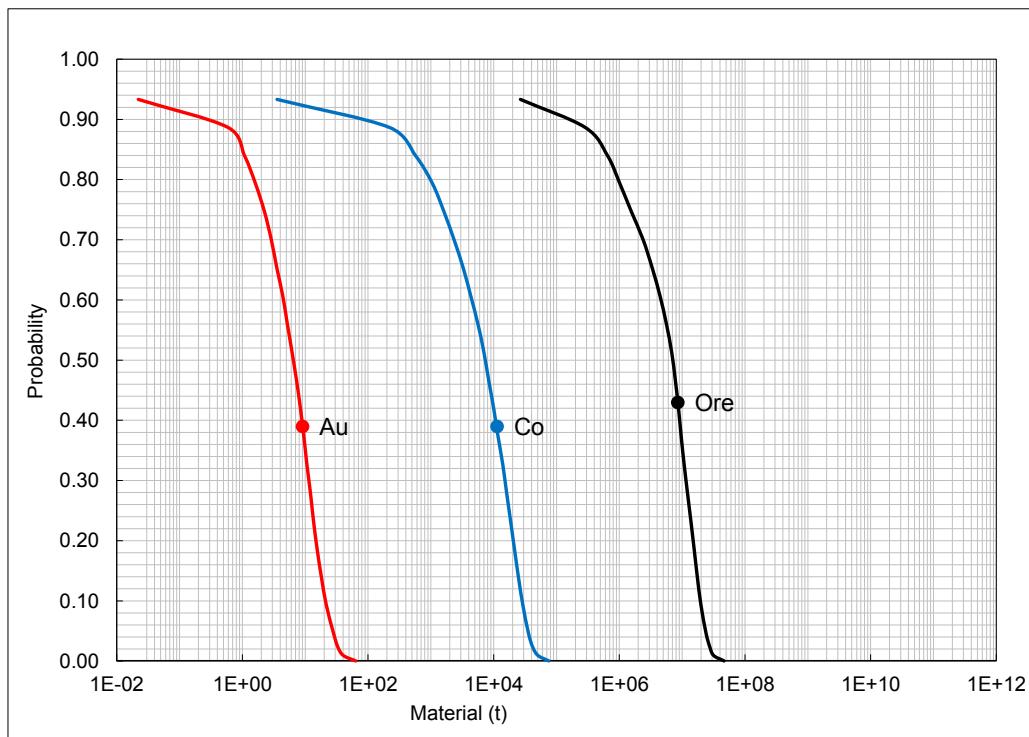


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Enontekiö Co-Au permissive tract. Labelled dots indicate mean values.

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Co ASSESSMENT FOR THE TRACT KAINUU Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Kainuu Co-Au permissive tract is located in central Finland in Puolanka, Paltamo, Pudasjärvi, Hyrynsalmi, Ristijärvi, Kajaani and Sotkamo municipalities (Fig. 1). The tract extends north of the city of Kajaani and Oulujärvi Lake, south-east of the village of Pudasjärvi and south-west of the vil-

lage of Taivalkoski. The UTM map sheets containing the tract are S511, R522, R524, R521, R512, R514, R511, R513, Q521, Q522, Q523 and Q524. The Co-Au resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Kainuu Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
29/05/2018	1	1,076	Co Au	0 0 Co Au	15,000 12 Co Au

t – metric ton

DELINeATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of the supracrustal sequence of the Palaeoproterozoic East and Central Puolanka Groups, and the 2.44–1.89 Ga dykes within these units. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic groups were excluded from the tract. The tract is bounded by Archaean TTG rocks and by the Kajaani granite

suite granites and migmatites in the west, and by the Palaeoproterozoic Nuasjärvi group rocks in the south. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-explored Kuusamo-type Co-Au deposits within the Kainuu Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Kainuu Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Content of metal (t)	Reference
<hr/>							

Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No Kuusamo-type Co-Au occurrences are known within the tract (Table 3).

Table 3. Significant Kuusamo-type Co-Au occurrences in the Kainuu Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
<hr/>					

Ma – million years

Exploration history

Exploration activities for the Kainuu Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Kainuu Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observation and boulder survey	Partly yes	Outokumpu	1960s–1980s
	Outcrop observation and boulder survey	Partly yes	GTK	1965–2017
Geochemical surveys	Nationwide systematic till survey, 277 points	Yes	GTK	1983–1987
	Line till geochemistry, tot. 2499 points	Yes	GTK	1975–1978
	Regional lake sediments, tot. 130 points	Yes	GTK	1975–1976
	Organic sampling tot. 345 points	Yes	GTK	1978–1981
	Inorganic sampling, tot. 319 points	Yes	GTK	1978–1981
Airborne geophysical surveys	Low-altitude airborne magnetic, electromagnetic and radiometric surveys		GTK	1970s–2000s
Ground geophysical surveys	Magnetic survey, profile surveys, tot. 542 km ²		GTK	1970s
	Gravimetric survey, profile surveys, tot. 283 km ²		GTK	1970s–1980s
	Magnetic surveys, tot. 4.8 km ²		Outokumpu	
Drilling	Targeting geochemistry, percussion drilling, tot. 3552 points	Partly yes	GTK	1960s–2000s
	Targeting geochemistry, percussion drilling, tot. 21 points	Yes	Outokumpu, Lapin Malmi, Rautaruukki	1980s
	74 DDH, tot. 3817.55 m	Partly yes	GTK	1960s–2000s
	6 DDH, tot. 662.33m	No data	Outokumpu	1963

DDH – diamond drill hole; GTK – Geological Survey of Finland

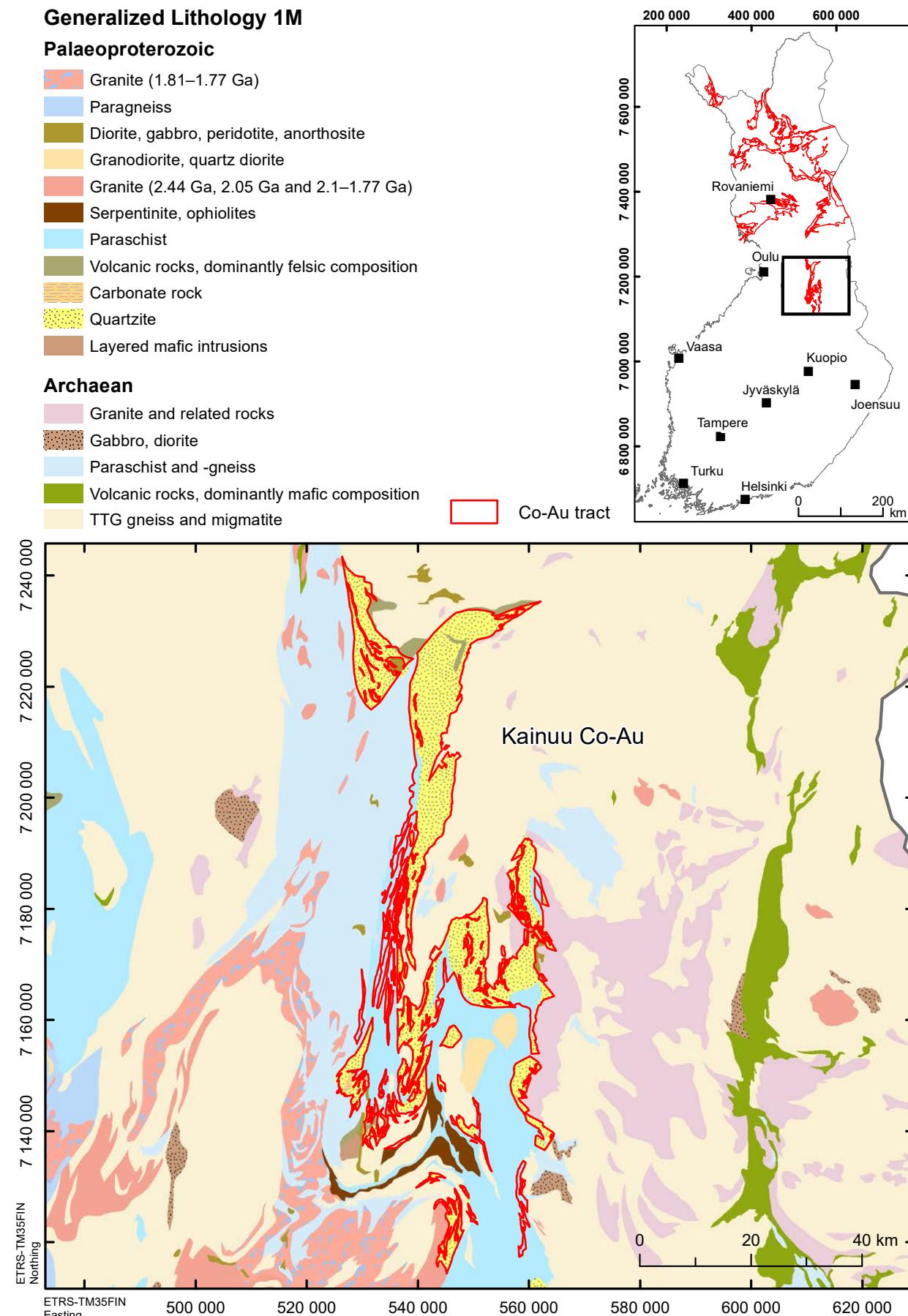


Fig. 1. Location of the Kainuu Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Kaiuu Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Kainuu Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP, http://gtkdata GTK.fi/Kalliopera/index.html
	Reports and publications		Laajoki (1986, 1991, 2005), Laajoki et al. (1989), Laajoki & Tuisku (1990), Strand (1988, 1993, 2005), Strand & Laajoki (1993, 1999), Evins & Laajoki (1997), Strand & Köykkä (2012)
Mineral occurrences	Geological Survey of Finland in-house database		http://gtkdata GTK.fi/mdae
	Reports		Tontti (2012)
Geo-chemistry	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports and publications		Kontoniemi et al. (2007), Kurki, J. (1987)
Geophysics	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
Exploration	Reports		Ervamaa (1976), Kontoniemi et al. (2007), Levin (2014)
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

Kuusamo-type Co-Au deposits or occurrences have not been detected within the tract area. The geology of the Kainuu tract is roughly similar to that in the Kuusamo tract. However, except for a few cobalt-bearing glacial boulders, no indications of mineralisation are known within the Kainuu tract, despite the exploration activities. On the other hand, past exploration within the tract focused mostly on industrial minerals, iron and uranium. The area of

the tract is large, so there is ample room for undiscovered mineralisation. Due to the small amount of available information, the uncertainty concerning the possibly existing undiscovered deposits within the tract is large, and no consensus was reached in the discussions. The mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Kainuu Co-Au permissive tract.

Mean undiscovered deposit estimate Summary statistics						Area (km ²)	Deposit density (N/km ²)				
N90	N50	N10	N05	N01	N _{und}	S	Cv%	N _{known}	N _{total}		
1	5	15			6.7	5.1	76	0	6.7	1076	0.0062

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	0	2	10		
Individual 2	1	8	20		
Individual 3	3	8	30		
Individual 4	0	4	10		
Individual 5	1	4	8		
Individual 6	0	3	10		
Mean	1	5	15		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and the total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Kainuu Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	0	220	11,000	37,000	47,000	15,000	0.40	0.07
Au (t)	0	0.62	8.7	29	36	12	0.40	0.07
Rock (Mt)	0	0.29	8.9	27	32	12	0.41	0.07

Mt – million metric tons; t – metric ton

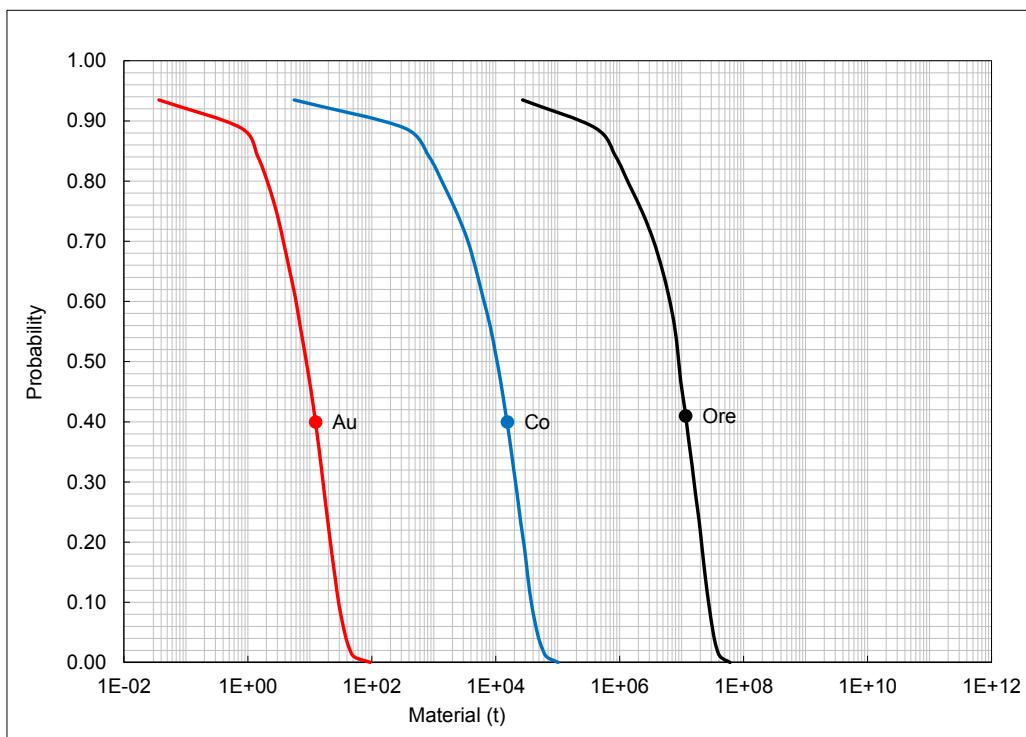


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Kainuu Co-Au permissive tract. Labelled dots indicate mean values.

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Co ASSESSMENT FOR THE TRACT KITTIÄ-KOLARI Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Kittilä-Kolari Co-Au permissive tract is located in northern Finland, in the municipalities of Kolari, Kittilä and Sodankylä (Fig. 1). The 1:50,000 UTM map sheets are U414, U421, U423, U424, U442, U441, and U443. The Co resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Kittilä-Kolari Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
14/8/2018	1	1,279	Co 0 Au 0	Co 9,300 Au 7.3	Co 5,400 Au 5

t – metric ton

DELINEATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of the 2.44–2.0 Ga supracrustal sequence of Kuusamo, Sodankylä and Savukoski Group rocks. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic groups were excluded from the tract. In the west, the tract is bounded by the border between Finland and Sweden. The northern boundary is defined by the

tectonic contact to the c. 2.05 Ga Kittilä Suite. In the south the tract is bound by the <1.91 Ga Proterozoic gneisses and Archean rocks. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-known Kuusamo-type Co-Au deposits within the Kittilä-Kolari Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Kittilä-Kolari Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Content of metal (t)	Reference
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Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No Kuusamo-type Co-Au occurrences are known within the tract (Table 3). Seven IOCG-style Fe-Cu(-Au) deposits and occurrences, with elevated cobalt contents, are known from the western part of the tract. Two of these (Rautuvaara and Hannukainen) have been mined. Twenty-one orogenic gold deposits and occurrences are known

within the tract. Of these, three (Saattopora, Hirvilavanmaa and Kutuvuoma) have been mined. Most of the orogenic gold occurrences are also enriched in copper and cobalt. Eight VMS-style deposits and occurrences, some with elevated cobalt content, are known within the tract.

Table 3. Significant Kuusamo-type Co-Au occurrences in the Kittilä-Kolari Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
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Ma – million years

Exploration history

Exploration within the tract has focused on iron, base metals, uranium and gold. Exploration activities for the Kittilä-Kolari Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Kittilä-Kolari Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observations and boulder survey	Partially yes	Suomen Malmi	1950s–1960s
	Outcrop observations and boulder survey	Yes	Rautaruukki	2060s–1980s
	Outcrop observations and boulder survey	Yes	Outokumpu	1960s–2000s
	Outcrop observations and boulder survey	Yes	GTK	1960s–today
Geochemical surveys	Nationwide till survey; 312 samples	Yes	GTK	1972–1991
	Targeting till geochemistry; 8475 samples	Yes	GTK	1972–1981
	Line till geochemistry; 40662 samples	Partially yes	Outokumpu	1970s–2000s
	Line till geochemistry; 48268 samples	Partially yes	Rautaruukki, Lapin Malmi	1960s–1980s
Airborne geophysical surveys	High-resolution, low-altitude airborne magnetic, electromagnetic and radiometric surveys		GTK	1976–2004
Ground geophysical surveys	Systematic gravimetric 102.9 km ²		GTK	1972–1976
	Systematic magnetic, 770 km ²		GTK	1968–1999
	Systematic slingram, 595 km ²		GTK	1972–1999
	Systematic IP, 10.7 km ²		GTK	1986–1990
	Systematic VLF, 118 km ²		GTK	1987–2003
	Systematic magnetic, 209.8 km ²		Outokumpu	1970s–1990s
	Systematic gravimetric, 23.4 km ²		Outokumpu	1970s–1990s
	Systematic VLF, 29.3 km ²		Outokumpu	1970s–1990s
	Systematic slingram, 220.0 km ²		Outokumpu	1970s–1990s
	Systematic IP, 2.86 km ²		Outokumpu	1970s–1990s
Drilling	Magnetic and IP survey		Firefox Gold	2018
	656 DDH, 39513 m	Partly yes	GTK	1960s–2018
	907 DDH, 104663 m	Partly yes	Outokumpu	1968–1995
	63 DDH, 7273 m	Partly yes	Lapin Malmi	1964–1991
	266 DDH, 33246 m	Yes	Rautaruukki	1959–1987
	47 DDH, 7095 m	Yes	Taranis Resources	2006–2011
	Diamond drilling	Yes	Firefox Gold	2018–

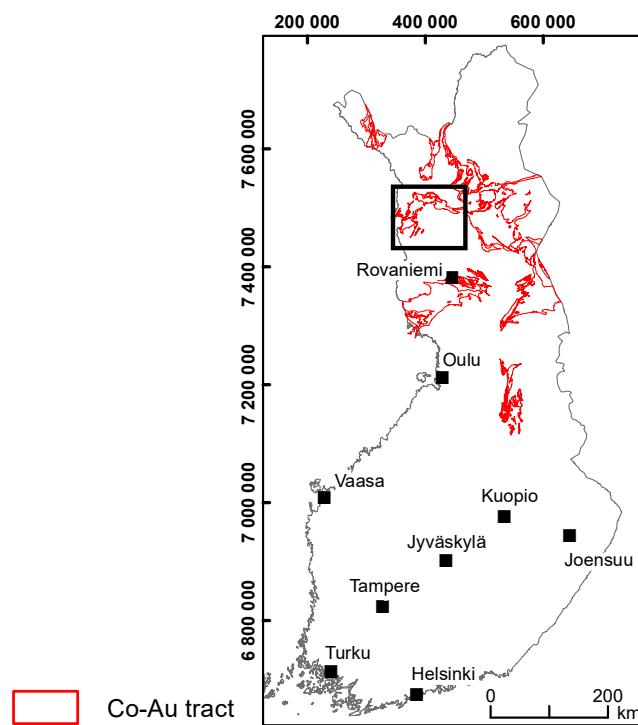
DDH – diamond drill hole; GTK – Geological Survey of Finland

Generalized Lithology 1M**Palaeoproterozoic**

- Diorite, gabbro, peridotite, anorthosite
- Granodiorite, quartz diorite
- Granite (2.1–1.79 Ga)
- Serpentinite, ophiolites
- Parachist
- Volcanic rocks, dominantly mafic composition
- Carbonate rock
- Quartzite

Archaean

- Parachist and -gneiss
- Volcanic rocks, dominantly mafic composition
- Volcanic rocks, dominantly felsic composition
- TTG gneiss and migmatite



Co-Au tract

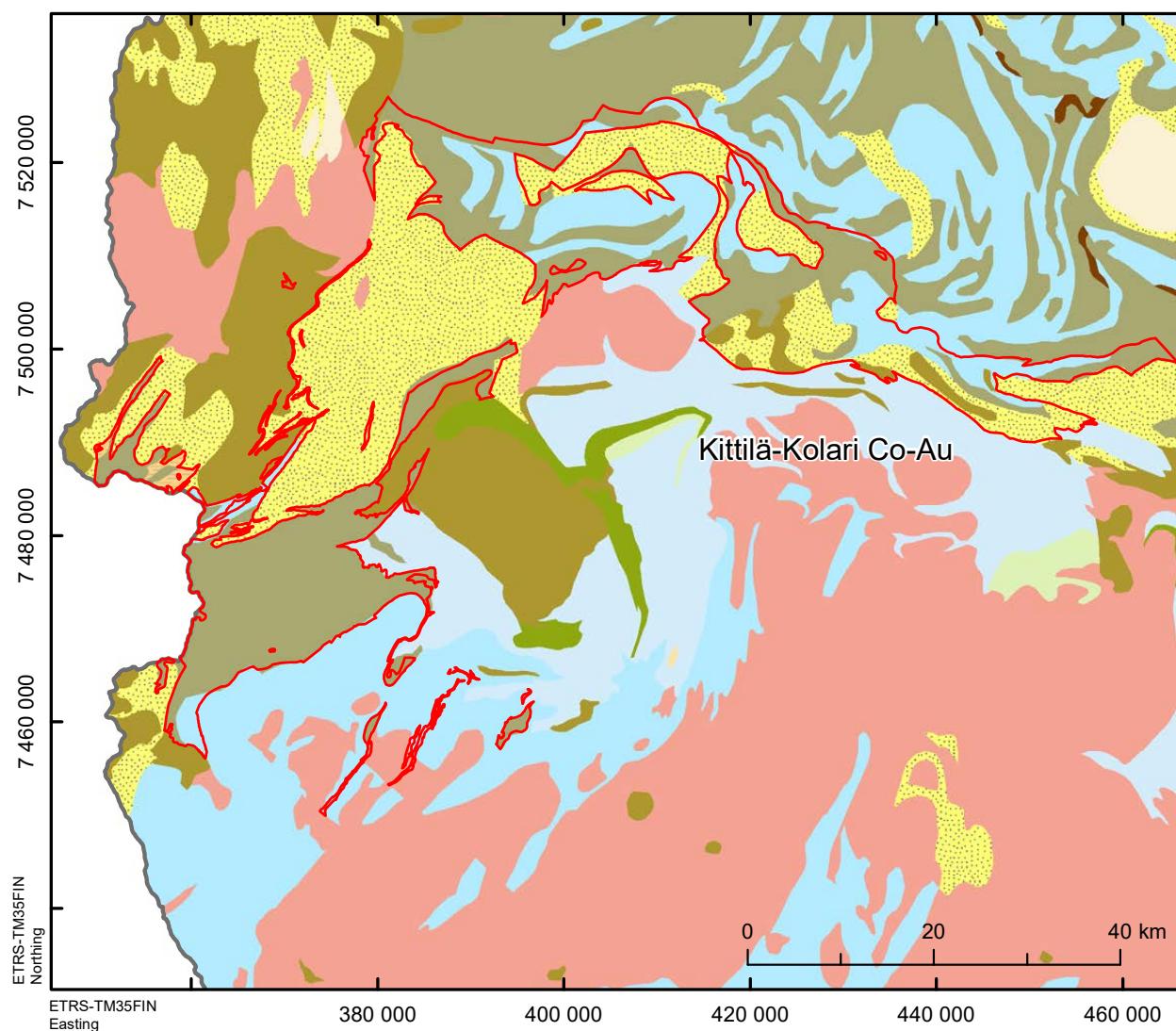


Fig. 1. Location of the Kittilä–Kolari Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Kittilä-Kolari Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Kittilä-Kolari Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP
	Reports and publications		Rastas (1984), Väänänen (1984, 1988, 1992), Mänttäri (1995), Lehtonen et al. (1998), Väisänen (2002), Hölttä et al. (2007), Patison (2007)
Mineral occurrences	Geological Survey of Finland in-house database		http://gtkdata GTK.fi/mdae
	Reports		Hiltunen (1982), Inkinen (1985, 1991a, 1991b, 1992a, 1992b), Lång (1986), Härkönen & Keinänen (1989), Keinänen & Salmirinne (2003), Korkalo (2006), Eilu et al. (2007, 2012), Holma & Keinänen (2007), Hulkki & Keinänen (2007), Niiranen et al. (2007)
Geochemistry	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports and publications		Wennevirta (1972), Kokkola (1975), Salminen (1995), Lehmuspelto et al. (2009), Pulkkinen & Sarala (2009)
Geophysics	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Eskola (1972), Turunen (1987), Lanne (1995), Keinänen & Salmirinne (2003)
Exploration	Reports		Inkinen (1985, 1991a,b, 1992a,b), Hugg (1987a,b, 1991a,b,c), Keinänen (1990, 2002), Anttonen (1992, 1994, 1995), Korvuo (1997a,b), Firefox Gold (2019)
	National drill core archive, Loppi		https://www GTK.fi/en/research-infrastructure/national-drill-core-archive/
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

The bedrock of the Kittilä-Kolari tract consists of a 2.44–2.05 Ga supracrustal sequence permissive for Kuusamo-type deposits. Extensive and locally intense alteration similar to what has been described in association with Kuusamo-type deposits occurs throughout the tract. However, for the most part the supracrustal sequence within the tract repre-

sents a higher sequence with deeper water environment than that of the Kuusamo area. Exploration activity within the Kittilä-Kolari tract has been high, but has been focused on orogenic gold, VMS and IOCG deposits, and not the Kuusamo-type. A large number of orogenic gold deposits and occurrences has been discovered within the tract and,

in addition, a number of IOCG-style deposits and VMS-style deposits. Elevated cobalt grades have been reported from a number of known gold and base metal deposits and occurrences. The overall potential of the tract was considered relatively low. Within the tract the potential is highest in the east-

ern part, which is geologically the most similar to the Kuusamo area. No consensus of the number of undiscovered deposits was reached in the discussion. The mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Kittilä–Kolari Co-Au permissive tract.

Mean undiscovered deposit estimate					Summary statistics				Area (km²)	Deposit density (N/km²)
N90	N50	N10	N05	N01	N _{und}	s	Cv%	N _{known}	N _{total}	
0	4	8			4.0	2.8	70	0	4.0	1,279 0.0031

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	0	3	10		
Individual 2	1	5	10		
Individual 3	0	6	10		
Individual 4	0	2	5		
Individual 5	0	3	6		
Individual 6	1	4	8		
Individual 7	1	3	10		
Mean	0	4	8		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Juhani Ojala, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and total mineralised rock.

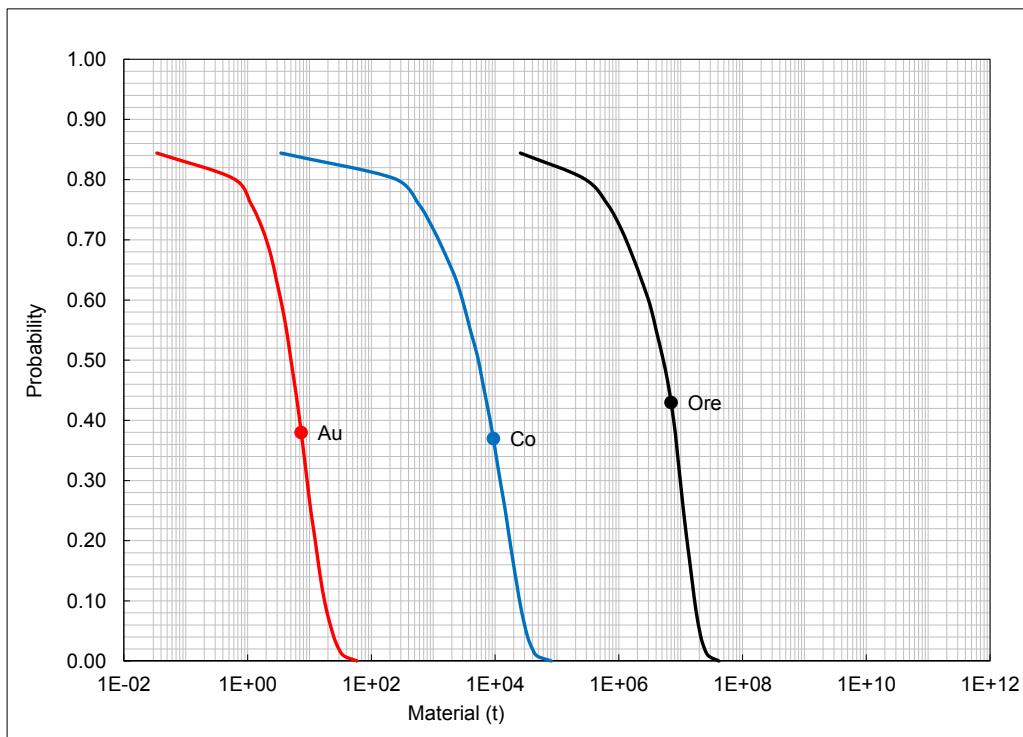


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Kittilä-Kolari Co-Au permissive tract. Labelled dots indicate mean values.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Kittilä-Kolari Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	0	0	5,400	25,000	32,000	9,300	0.37	0.16
Au (t)	0	0	5.0	18	23	7.3	0.38	0.16
Rock (Mt)	0	0	5.2	17	20	6.9	0.43	0.16

Mt – million metric tons; t – metric ton

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Co ASSESSMENT FOR THE TRACT KUUSAMO Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Kuusamo Co-Au permissive tract is located in northern Finland, in the municipalities of Salla, Kuusamo, Posio, and Pudasjärvi (Fig. 1). The 1:50,000 UTM map sheets are S521, S522, S523,

S541, S542, T513, T514, T523, T524, T531, and T541. The Cu-Au resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Kuusamo Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
29/6/2018	1	3,684	Co Au 19	Co 34,000 Au 27	Co 28000 Au 22

t – metric ton

DELINeATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of 2.44–2.0 Ga Kuusamo, Sodankylä and Savukoski Group supracrustal sequence and known examples of Kuusamo-type Co-Au deposits and occurrences in the area. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic groups were excluded from the tract. The tract covers an area known as Kuusamo Schist Belt, which

is a distinct subdomain of the Central Lapland Greenstone belt. The tract is bounded to the north-east by the border between Finland and Russia. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are 11 well-known Kuusamo-type Co-Au deposits within the Kuusamo Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Kuusamo Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Content of metal (t)	Reference
Apajalahti	579449	7335401		0.13	Au (g/t) Cu (%)	4.04 0.05	Lahtinen (1980)
Haarakumpu	570468	7368246		4.68	Co (%) Cu (%)	0.17 0.34	Vartiainen (1984)
Hangaslampi	598894	7352947		0.583	Au (g/t) Co (%)	3.6 0.07	Dragon Mining (2012)
Juomasuo Au	598681	7353837		2.371	Au (g/t) Co (%)	4.54 0.13	Dragon Mining (2014)
Juomasuo Co	598681	7353837		5.04	Au (g/t) Co (%)	0.13 0.12	Dragon Mining (2013, 2014)
Kouvervaara	582106	7335728		1.55	Au (g/t) Co (%)	0.38 0.01	Tarvainen (1985a), Vanhanen (1988)
Lemmon-lampi	581539	7337102		0.37	Au (g/t) Co (%) Cu (%)	0.35 0.23 0.52	Korkalo (1987)
Meurastuk-senaho	593755	7343820		0.892	Au (g/t) Co (%)	2.3 0.2	Dragon Mining (2014)
Pohjasvaara	599508	7352676		0.133	Au (g/t) Co (%)	3.77 0.09	Dragon Mining (2014)
Säynäjävaara	584539	7339247		0.423	Au (g/t) Co (%)	1.1 0.06	Tarvainen (1985b)
Sivakkaharju	591979	7342707		0.05	Au (g/t) Co (%)	7.2 0.03	Dragon Mining (2014)

Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

At least 15 partially explored Kuusamo-type Co-Au occurrences are known within the tract (Table 3).

Table 3. Significant Kuusamo-type Co-Au occurrences in the Kuusamo Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
Hangaspuro	598194	7353989		3 m @ 4 g/t Au, 14 m @ 0.14% Co, 1 m @ 1.9% Cu	Vahanen (1992, 2001)
Honkilehto	590035	7341513		0.5 m @ 29.5 g/t Au, 0.34% Cu, 0.15% Co	Pankka (1995)
Isoaho-1	599461	7351573		3 m @ 4 g/t Au	Vahanen (1992)
Isoaho-2	598953	7351749		3 m @ 4 g/t Au	Vahanen (1992)
Iso-Rehvi	594112	7345212		0.04 Mt @ 4 g/t Au, 0.05% Co, 0.1% Cu	Vahanen (1990a)
Kantolahti	590410	7347932		1 m @ 13.4 g/t Au, 3.7 m @ 0.2% Co	Pankka (2000)
Konttiaho	592831	7341647		15 and 5 m wide breccia pipes with 1–12 g/t Au, 200–1000 ppm U and Co; 8 m @ 10 ppm Au	Vahanen (1991b,c, 2001)
Kuusamon Hanhilampi	598358	7351620		5 m @ 3 g/t Au	Vahanen (1992a)
Lavasuo	586260	7361388		1 m @ 2 g/t Au	Inkinen (1987)
Murronmaa	589855	7339002		5 grab samples with 1–97 g/t Au	Vahanen (1990c)
Naatikka- lampi	589002	7333857		Chanel samples with 0.1–3.29% Cu, <290 ppm Co, <0.2 g/t Au	Lahtinen (1978)
Ollinsuo	585806	7335805		16 m @ 1.7 g/t Au, 0.11% Co, 0.12% Cu	Pankka (1989a)
Pohjaslampi	599048	7351853		4 m @ 4 g/t Au	Vahanen (1992)
Sakarinkaivu- lamminsuo	598933	7354250		2 m @ 2 g/t Au, 9 m 0.13% Co	Vahanen (1992)
Sarkanniemi	590840	7350390		up to 10 g/t Au in samples from outcrops	Pankka (1993)

Ma – million years

Exploration history

Exploration activities for the Kuusamo Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Kuusamo Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observations and boulder survey	Yes	GTK	1960–
	Outcrop observations and boulder survey	Yes	Outokumpu Oy	1906s–1980s
Geochemical surveys	Nationwide till survey, 906 samples	Yes	GTK	1988–1989
	Line till sampling, 1732 samples	Yes	GTK	1979
	Targeting till sampling, 8088 samples	Yes	GTK	1970s–1990s
	Targeting till sampling, 4762 samples	Yes	Outokumpu Oyj	1980s–1990s
Airborne geophysical surveys	High-resolution, low-altitude air-borne magnetic, EM and radiometric surveys		GTK	1980–2000
Ground geophysical surveys	Systematic gravimetric survey, 40 km ²		GTK	1985–1997
	Systematic magnetic survey, 848 km ²		GTK	1973–2012
	Systematic slingram survey, 742 km ²		GTK	1972–1990
	Systematic IP survey, 124 km ²		GTK	1986–2001
	Systematic VLF survey, 238 km ²		GTK	1982–2012
	Systematic magnetic survey, 36 km ²		Outokumpu Oyj	1960s–1990s
	Systematic gravimetric survey, 6 km ²		Outokumpu Oyj	1970s
	Systematic VLF survey, 10 km ²		Outokumpu Oyj	1980s–1990s
	Systematic IP survey 5 km ²		Outokumpu Oyj	1970s–1990s
Drilling	Systematic slingram survey 27 km ²		Outokumpu Oyj	1970s–1990s
	598 DDH, 34800 m	Partly yes	GTK	1968–2014
	105 DDH, 9899 m	Yes	Outokumpu Oyj	1960–1994
	38 DDH, 4023 m	Yes	Lapin Malmi Oyj	1970–1985
	8 DDH, 655 m	Yes	Belvedere Resources	2005
	14 DDH, 530 m	Yes	Ilmari Exploration Oy	2004–2007
	3 DDH, 60 m	Yes	Malmikaivos Oy	1996
	3 DDH, 278 m	Yes	Rautaruukki Oy	1963
	>100 DDH m	Yes	Dragon Mining	2003–2016
	8 DDH, 655 m	?	Belvedere Resources	2005

DDH – diamond drill hole; GTK – Geological Survey of Finland

Generalized Lithology 1M**Palaeozoic**

Devonian alkaline rock

Palaeoproterozoic

Quartz-feldspar gneiss

Diorite, gabbro, peridotite, anorthosite

Granite

Volcanic rocks, dominantly mafic composition

Carbonate rock

Quartzite

Volcanic rocks, dominantly felsic composition

Layered mafic intrusions

Archaean

Carbonatite

Granite and related rocks

Paraschist and -gneiss

Volcanic rocks, dominantly mafic composition

TTG gneiss and migmatite

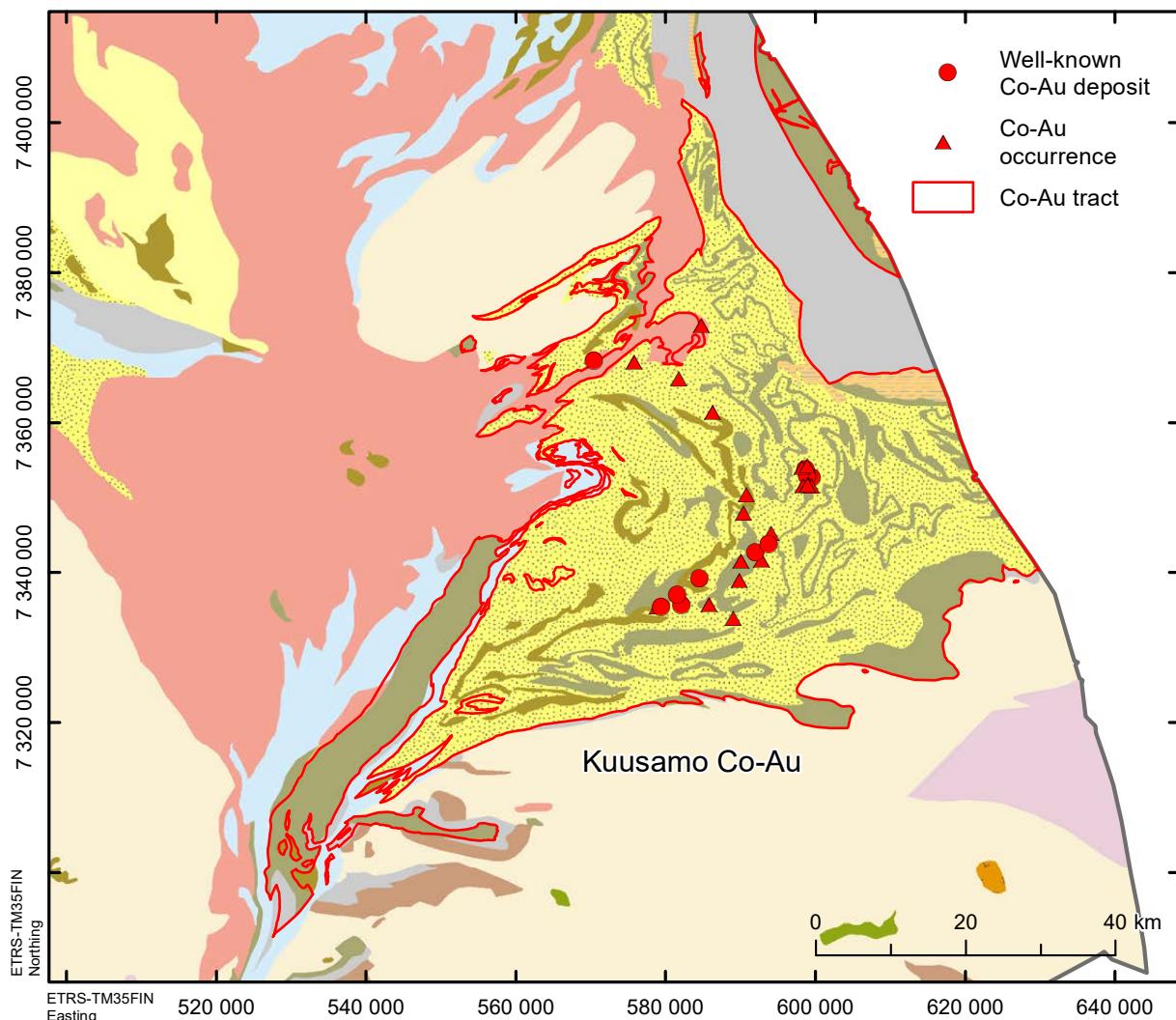
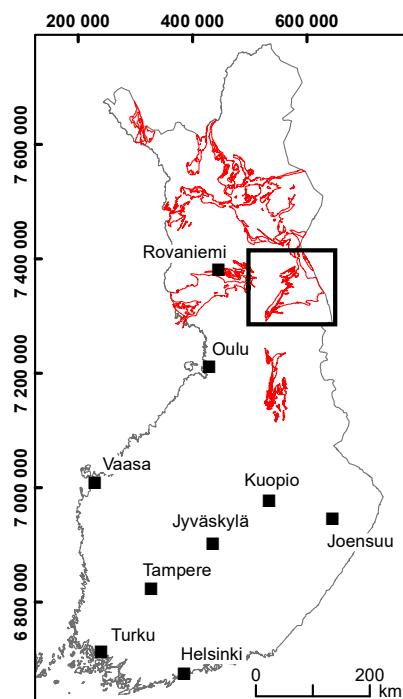


Fig. 1. Location of the Kuusamo Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Kuusamo Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Kuusamo Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP
	Reports and publications		Silvennoinen (1972, 1985, 1991, 1992, 1993), Vanhanen (1991a, 2001), Pankka et al. (1991), Pankka & Vanhanen (1992), Arkimaa (1997), Räsänen & Vaajoki (2001), Laajoki & Wanke (2002), Nironen (2017), Pohjolainen et al. (2017)
Mineral occurrences	Geological Survey of Finland in-house database		http://gtkdata GTK.fi/mdae
	Reports		Kuronen (1981), Tarvainen (1985), Roos (1987), Vanhanen (1988a,b, 1989a,b,c, 1990a,b,c, 1991a,b,c,d,e, 1992a,b,c, 1997, 2001), Pankka (1989a,b, 1992, 1993, 1994, 1995, 1997b,c, 1999, 2000), Parkkinen (1989), Pankka et al. (1991), Pankka & Vanhanen (1992), Korteniemi (1993), Eilu et al. (2012), Dragon Mining (2014)
Geochemistry	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports and publications		Vartiainen (1985a), Vanhanen (1988a,b, 1989a, 1990c, 1991b,c,d, 1992a,b,c, 1997, 2001), Johansson & Nenonen (1990), Pankka (1994, 1995, 1997b), Lahtinen (1997)
Geophysics	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Vartiainen (1985a,b), Turunen (1989, 1990, 1991, 1995, 1996, 1997, 1999, 2000a,b), Inkinen (1987), Vanhanen (1988a,b, 1989b,c, 1990a,c, 1991b,c,d,e, 1992a,b,c, 1997), Pankka (1989a,b, 1993, 1994, 1995, 1997b,c, 2000), Hugg (1994), Airo (1999), Arkimaa (1997), Lahtinen (1997), Turunen et al. (2005), Strauss (2006a,b)
Exploration	Reports		Lahtinen (1980, 1993, 1997), Tarvainen (1985, 1986), Vartiainen (1985a,b), Inkinen (1987), Vanhanen (1988a,b,c, 1989a,b, 1990a,b,c, 1991b,c,d,e, 1992a,b,c, 1997), Pankka (1989a,b, 1994, 1995, 1997b,c, 1999, 2000), Parkkinen (1989), Turunen (1989, 1990, 1991, 1995, 1996, 1997, 1999, 2000a), Johansson & Nenonen (1990), Anttonen (1994), Hugg (1994, 1997), Strauss (2006a,b), Dragon Mining (2014)
	National drill core archive, Loppi		https://www GTK.fi/en/research-infrastructure/national-drill-core-archive/
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

Ten well-known Kuusamo-type Co-Au deposits (Juomasuo Au and Juomasuo Co were combined in the grade-tonnage model) and 15 partially explored occurrences are known within the tract. Exploration activity for Kuusamo-type deposits has been high in the area. Most of the discoveries have been initially made using radiometric methods, but significant parts of the tract area are covered by water and wetlands not suitable for radiometric measurements. Hence there is considerable potential in these parts. The exploration in the Kuusamo tract area has focused on surface and shallow parts, but

considerable potential exists in deeper parts of the tract. Also, in several of the 15 partially explored occurrences, the drilling has focused on shallow depths and it is likely that significant amounts of mineralised rock may occur at greater depth. This tract was considered to have the greatest potential in Finland, but consensus on the number of undiscovered deposits was not reached in the discussion. The mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Kuusamo Co-Au permissive tract.

Mean undiscovered deposit estimate						Summary statistics			Area (km ²)	Deposit density (N/km ²)
N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁	N _{und}	S	Cv%	N _{known}	N _{total}	
6	11	29			14	8.7	60	10	24	3,684 0.0065

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	10	20	40		
Individual 2	3	4	24		
Individual 3	10	16	30		
Individual 4	5	10	25		
Individual 5	5	10	20		
Individual 6	3	8	37		
Mean	6	11	29		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eili, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Kuusamo Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	2,000	5,000	28,000	70,000	82,000	34,000	0.42	0.02
Au (t)	3.2	6.2	22	55	65	27	0.43	0.02
Rock (Mt)	2.1	4.9	22	51	59	25	0.43	0.02

Mt – million metric tons; t – metric ton

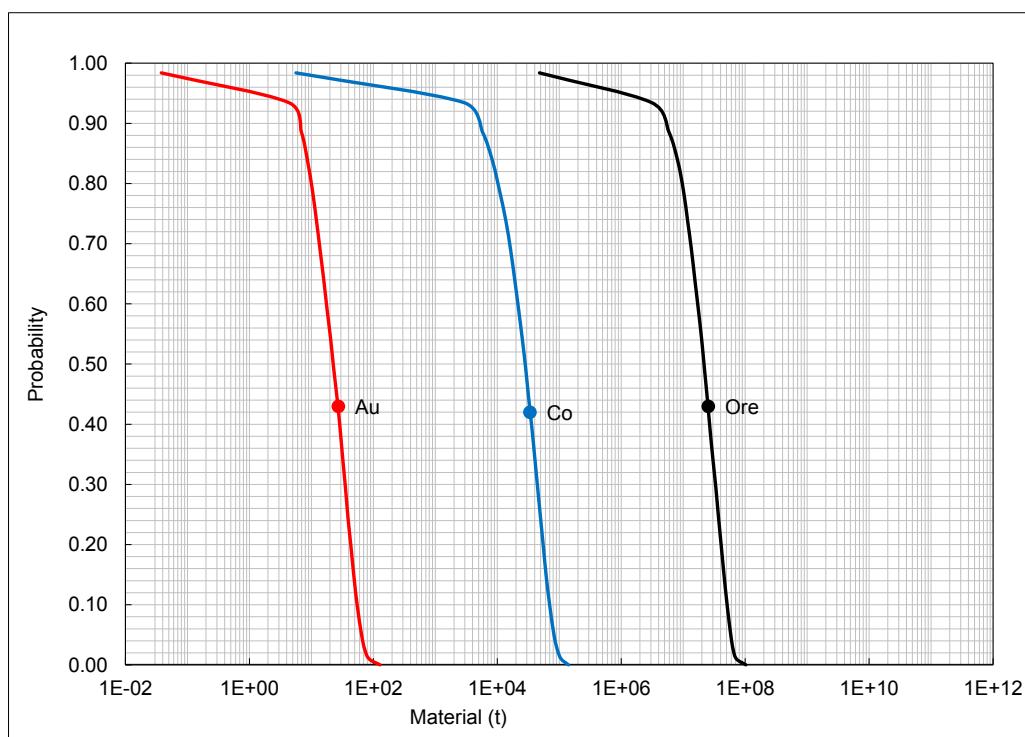


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Kuusamo Co-Au permissive tract. Labelled dots indicate mean values.

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Co ASSESSMENT FOR THE TRACT PELKOSENNIMEMI Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Pelkosenniemi Co-Au permissive tract is located in northern Finland, in the municipalities of Kemijärvi, Sodankylä, Pelkosenniemi, Salla and Savukoski (Fig. 1). The 1:100,000 KKJ map sheets containing the tract are 3624, 3642, 3643, 3644, 3713, 3714, 3731, 3732, 3733, 3734, 3741, 3743, 4621,

4622, 4624, 4711, 4712 and 4721. The 1:50,000 UTM map sheets are V511, U522, U443, U521, U523, U434, U512, U514, U433, U511, U513, T444, T522, T524 and T523. The Co-Au resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Pelkosenniemi Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
14/08/2018	1	5,611	Co 0 Au 0	Co 21,000 Au 17	Co 16,000 Au 14

t – metric ton

DELINeATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of the 2.44–2.0 Ga supracrustal sequence of Kuusamo, Sodankylä and Savukoski Group

rocks. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic groups were excluded from the tract. The tract is bounded

to the east and north-east by Archean rocks, and to the south and south-east by Central Lapland Granitoid complex granites and migmatites. The northern contact to the adjacent Sodankylä tract is defined by peak metamorphic gradient boundary between mid-amphibolite facies in the south

and mid greenschist facies in the south. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-known Kuusamo-type Co-Au deposits within the Pelkosenniemi Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Pelkosenniemi Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Contained metal (t)	Reference
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Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No Kuusamo-type Co-Au occurrences are known within the tract (Table 3). The ultramafic rock-hosted Sakatti Ni-Cu-PGE deposit within the tract has significant cobalt contents (Brownscombe et al. 2015). In addition, there are several other deposit types, many of which have assayed anomalous cobalt values (100s of ppm). East of the Pelkosenniemi town, there are several pyrite-dominated sulphide deposits (Vesilaskujänkä, Reposaari and Jauratsi) and a magnetite deposit (Rahkavaara), which have been explored primarily for their iron and base metal potential (Hiltunen 1970, Kerkkonen 1982, Roos 1982d, 1983a). The Vesilaskujänkä deposit has a non-compliant resource estimate of 1.8 Mt with 0.35% Cu, 0.02% Ni and 0.01% Co, and it

contains cobaltian pyrite with a cobalt content of about 2000 ppm. The Jauratsi deposit contains 22 Mt of pyrite-rich schist (17.8% Fe, 17.8% S), the Reposaari 26 Mt (15% Fe, 16% S) (Kerkkonen 1982, Roos 1983b). In addition, there are three Cu occurrences with elevated cobalt values within the tract (Iso-Povivaara, Kelujoki and Sodankylä kk). For the Iso-Povivaara vein-style Cu occurrence south of the Lokka reservoir, concentrations of up to 0.3% Co have been assayed in grab samples and about 1% Co in pyrite (Lahtinen and Rekola 1977, Karvinen 1983). Cobalt contents of up to 0.6% have been assayed in grab samples, and up 800 ppm in drill core, of the Kelujoki Cu occurrence (Karvinen 1982).

Table 3. Significant Kuusamo-type Co-Au occurrences in the Pelkosenniemi Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
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Ma – million years

Exploration history

Exploration activities (reported claims) for the Pelkosenniemi Co-Au tract are listed in Table 4.

Table 4. Exploration history (reported claims) for the Pelkosenniemi Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observation and boulder survey	Yes	GTK	1960s–present
	Outcrop observation and boulder survey	Yes	Outokumpu Oyj	1960s–2000s
	Outcrop observation and boulder survey	Yes	Anglo American	2004–present
	Outcrop observation and boulder survey	Yes	FQM FinnEx	2010–2015
	Outcrop observation and boulder survey	Yes	Magnus Minerals	2011–present
	Outcrop observation and boulder survey	Yes	Antofagasta Minerals (joint venture with Magnus Minerals)	2012–2015
	Outcrop observation and boulder survey	?	Stonerol Oy	2012–
	Outcrop observation and boulder survey	?	Aurion Resources	2015–present
	Outcrop observation and boulder survey	?	Rautaruukki, Lapin Malmi	1960s–1980s
	Outcrop observation and boulder survey		Risto Jurvakainen	1995–1997
Geochemical surveys	Nationwide till survey, 1318 samples	Yes	GTK	1971–1991
	Targeting line till geochemistry, 53000 samples	Yes	GTK	1972–1980s
	Targetted till geochemistry, 9520 samples	Yes	GTK	1972–2000s
	Line till geochemistry, 3007 samples	Partially yes	Rautaruukki, Lapin Malmi	1970s–2000s
	Indicator/heavy mineral, 295 samples		Outokumpu Oyj	1990–2000s
	Base of till sampling, 84 samples,		Anglo American	2004–2017
	Surface soil, C horizon till sampling, 260 samples	Yes	Magnus Minerals	2013
	Base of till sampling, 1002 samples	Yes	Magnus Minerals	2014–2015
	High resolution, low-altitude airborne magnetic, electromagnetic and radiometric surveys		GTK	1975–2008
	High-resolution airborne EM, magnetic, gravity surveys		Anglo American	2010–2014
Airborne geophysical surveys	VTEM		Magnus Minerals	2013

Table 4. Cont.

Theme	Type of work	Co analysed	Organisation	When carried out
Ground geophysical surveys	Systematic gravity surveys, 265 km ²		GTK	1979–2000
	Systematic magnetic, 598 km ²		GTK	1972–2006
	Systematic Slingram, 31 km ²		GTK	1978–1996
	Systematic MIN-Max, 14 km ²		GTK	1991
	Systematic IP, 2.5 km ²		GTK	1998–2001
	Systematic VLF/VLF-R, 439 km ²		GTK	1988–2015
	Systematic magnetic, 1.5 km ²		Outokumpu Oyj	1970s–1990s
	Systematic slingram, 1.5 km ²		Outokumpu Oyj	1970s–1990s
	Magnetic surveys		RTZ Mining and Exploration	1994–1995
	Magnetic surveys		Magnus Minerals	2011–2014
Drilling	EM sligram and magnetic surveys, 3,8 line km		Anglo American	2004–2005
	EM and magnetic surveys, 15 line km		FQM FinnEx	2014–2015
	21 DDH, 436m	Yes?	Suomen Malmi Oy	1966–1967
	629 DDH, 33871 m	Yes	GTK	1974–2007
	80 DDH, 9148m	Yes?	Outokumpu Oy/ Lapin Malmi/ Rautaruukki	1957–1988
	18 DDH, 409 m	No	Kemijoki Oy	1975–1976
	21 DDH, 1232 m	No?	RTZ Mining and Exploration	1994–1995
	43 DDH, 11659 m	Yes	Anglo American	2005–2015
	5 DDH, 960 m	Yes	FQM FinnEx	2014–2015
	5 DDH, 1073 m	Yes	Magnus Minerels	2014–2015
	2 DDH 164 m	?	Stonerol Oy	2015

DDH – diamond drill hole; GTK – Geological Survey of Finland

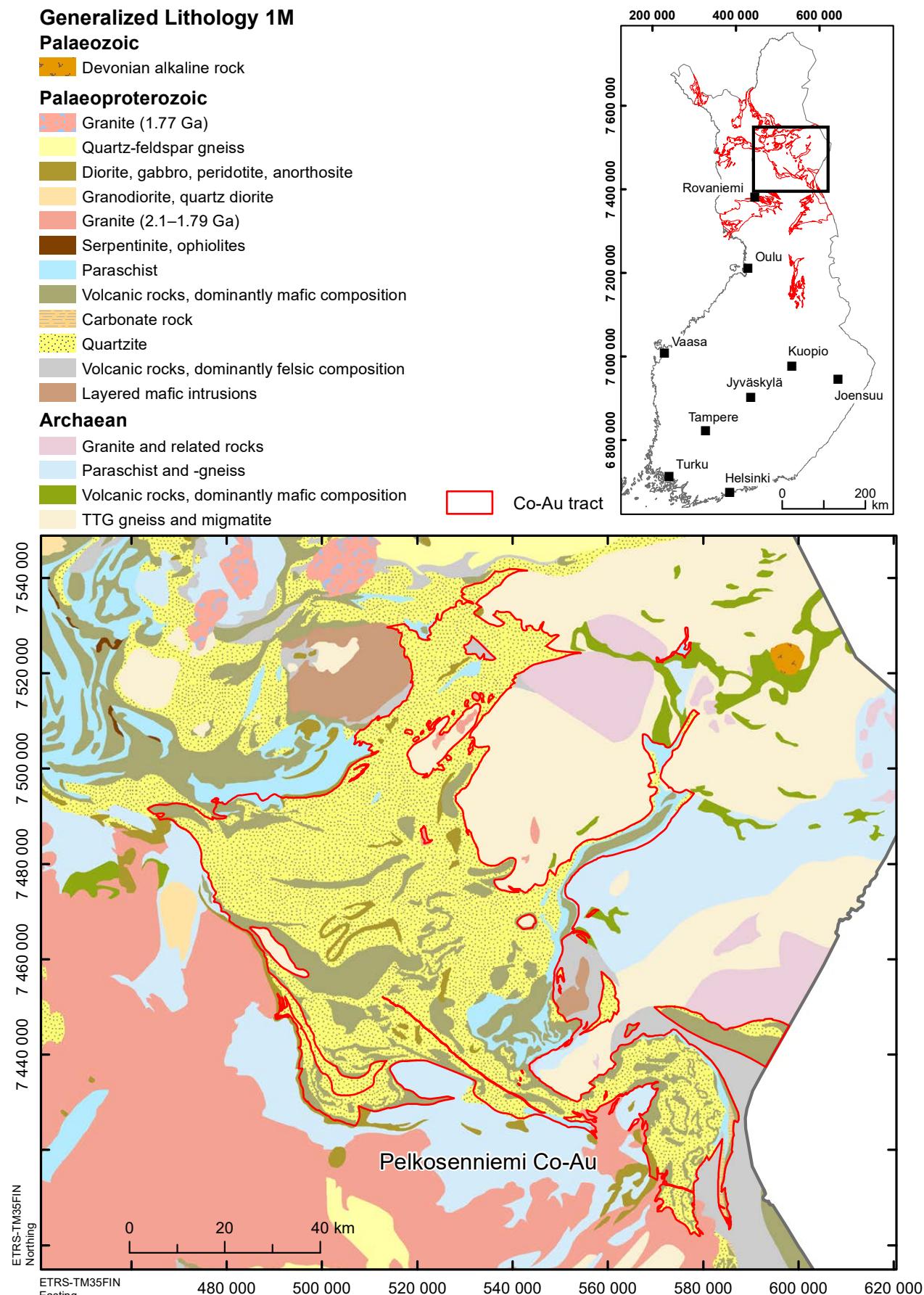


Fig. 1. Location of the Pelkosenniemi Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Pelkosenniemi Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Pelkosenniemi Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP
	Reports and publications		Saverikko (1980), Saverikko & Manninen (1981), Lehtonen et al. (1998), Räsänen (2005), Hölttä et al. (2007)
Mineral occurrences	Geological Survey of Finland in-house database		http://gtkdata GTK.fi/mdae
	Reports		Hiltunen (1970), Karvinen (1982, 1983), Kerkkonen (1981, 1982), Roos (1982d, 1983a,b), Karvinen & Sandgren (2010), Brownscombe et al. (2015)
Geochemistry	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports and publications		Pulkkinen (1970), Hirvas (1972), Horvas & Pulkkinen (1975), Lehmuspelto (1978), Lehmuspelto & Vuojärvi (1980, 1983), Pulkkinen et al. (1991), Sarala et al. (2008)
Geophysics	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Turunen (2004)
Exploration	Reports		Airas (1975), Lahtinen & Rekola (1977), Rossi (1977), Korvuo (1978), Lahtinen (1978, 2003), Nuutilainen (1978), Hiltunen (1979), Karvinen (1982, 1983), Vuotovesi (1985), Inkinen (1990a,b), Roos (1982a,b,c,d, 1983a,b, 1988), Hugg (1990), Mutanen (1982, 1999, 2003), Juopperi (1994), Sims (1996a-y), Hanski (1998), Isomaa (1999), Pankka (2001), Långbacka (2007), Haverinen (2014, 2015a,b), FQM FinnEx (2016), Mikkola & Reynolds (2016a,b, 2017a,b,c)
	National drill core archive, Loppi		https://www GTK.fi/en/research-infrastructure/national-drill-core-archive/
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

No Kuusamo-type Co-Au deposits are known within the tract. The tract has a similar stratigraphy as the Kuusamo tract, for which it forms a direct continuation to the north. The tract covers an extensive area, and exploration intensity has been low within large parts of it. About 10–15 glacial erratic boulders

with elevated cobalt content (>1000 ppm Co) are known from the area. On the other hand, despite the exploration, no Kuusamo-type targets have been identified, and larger-scale albitisation is known from only parts of the area (although this might be an effect of the metamorphic grade; scapolite

is known to occur also). Consensus on the number of undiscovered deposits was not reached in the discussion. The mean values of the numbers given

by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Pelkosenniemi Co-Au permissive tract.

Mean undiscovered deposit estimate Summary statistics							Area (km ²)	Deposit density (N/km ²)		
N90	N50	N10	N05	N01	N _{und}	S	Cv%	N _{known}	N _{total}	
2	8	18			9.1	5.7	63	0	9.1	5,611 0.0016
Estimated number of undiscovered deposits										
Estimator										
N ₉₀										
Individual 1										
3										
Individual 2										
2										
Individual 3										
2										
Individual 4										
2										
Individual 5										
2										
Individual 6										
2										
Individual 7										
Mean										
2										
8										
18										

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Juhani Ojala, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and the total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Pelkosenniemi Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	86	1,000	16,000	46,000	57,000	21,000	0.42	0.04
Au (t)	0.33	1.7	14	37	45	17	0.42	0.04
Rock (Mt)	0.13	1.0	13	33	39	16	0.44	0.04

Mt – million metric tons; t – metric ton

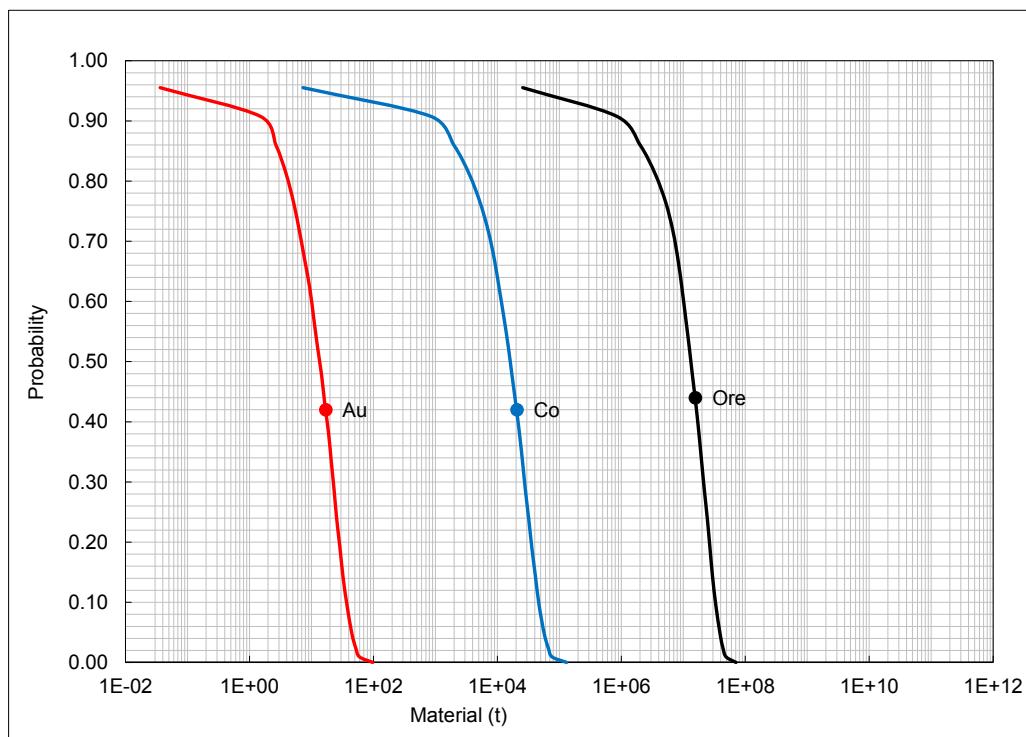


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Pelkosenniemi Co-Au permissive tract. Labelled dots indicate mean values.

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Co ASSESSMENT FOR THE TRACT PERÄPOHJA Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Peräpohja Co-Au permissive tract is located in northern Finland, in Ylitornio, Tornio, Kemi, Keminmaa, Tervola, Rovaniemi and Kemijärvi municipalities. The tract extends for about 75 km east and 100 km south-west of the city of Rovaniemi

(Fig. 1). The UTM map sheets containing the tract are S414, S423, S424, S441, S442, S444, T413, T431, T432, T433, T434, T443, T511, T512, T521 and T522. The Co-Au resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Peräpohja Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
29/05/2018	1	4,634	Co Au	0 0 Co Au 28,000 22	22,000 18

t – metric ton

DELINeATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of the Palaeoproterozoic Kivalo Group supracrustal sequence and 2.44–1.89 Ga dykes within these units. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic

groups were excluded from the tract. The tract is bounded by Archaean TTG rocks and 2.4 Ga layered intrusions to the south, by the Central Lapland Granitoid Complex granites and migmatites and Martimo Group rocks to the north and east, and by

the Finnish–Swedish border and the Baltic Sea to the west and south-west. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely simi-

lar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-explored Kuusamo-type Co-Au deposits within the Peräpohja Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Peräpohja Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Content of metal (t)	Reference
None							

Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No Kuusamo-type Co-Au occurrences are known within the tract (Table 3). Epigenetic occurrences detected within the tract include: 1) Ten skarn-like iron deposits in the Misi area, 2) five Au±Cu occurrences of possibly orogenic type, 3) two to five

Au±Co, U occurrences in the Rompas–Rajapalot area (northern part of the tract, undefined genetic class), and 4) the Vähäjoki (Fe–Au–Cu–Co) IOCG deposit (Rouhunkoski & Isokangas 1974, Liipo & Laajoki 1991, Eilu et al. 2015, Ranta et al. 2018).

Table 3. Significant Kuusamo-type Co-Au occurrences in the Peräpohja Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
None					

Ma – million years

Exploration history

Exploration activities for the Peräpohja Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Peräpohja Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observations and boulder survey	Partly yes	Outokumpu Mining Oy	1960s–1980s
	Outcrop observations and boulder survey	Not known	Otanmäki, Rautaruukki	Late 1970s
	Outcrop observations and boulder survey	Partly yes	GTK	1946–2007
	Outcrop observations and boulder survey	Yes	Inmet	2006–2008
	Outcrop observations and boulder survey	Yes	AREVA	2007–2009
	Outcrop observations and boulder survey	Partly yes	Mawson	2010–
Geochemical surveys	Nationwide till survey, systematic, 1115 points	Yes	GTK	1981–1990
	Line till geochemistry, tot. 3087 points	Yes	GTK	1981–1982
	Targeting geochemistry, percussion drilling, tot. 12100 points	Yes	GTK	1982–1997
	Targeting geochemistry, percussion drilling, tot. 707 points	Yes	Outokumpu, Lapin Malmi, Rautaruukki	1970s–1980s
	Organic sampling, tot. 1972 points	No	GTK	1970s–1980s
	Inorganic sampling, tot. 192 points	No	GTK	1981–1983
Airborne geophysical surveys	Till samples, tot. 758 points, organic soil samples, tot. 1151 points, BOT, 900 points, 23 line km		Mawson	2010–
	Low-altitude airborne magnetic, electromagnetic and radio-metric surveys		GTK	1980s–2000s
	Magnetic, radiometric surveys		Rautaruukki	1970s
	Airborne gravimetry		Inmet	2010
	Magnetic, VTEM and radiometric surveys		Mawson	2010s

Table 4. Cont.

Theme	Type of work	Co analysed	Organisation	When carried out
Ground geophysical surveys	Magnetic profile surveys, tot. 217 km ²	GTK		1970s–2000s
	Gravimetric profile surveys, tot. 161 km ²	GTK		1960s–2000s
	IP survey, profile surveys, tot. 47 km ²	GTK		1990s–2000s
	Slingram surveys, tot. 32 km ²	GTK		1989
	MaxMin systematic surveys, tot. 10 km ²	GTK		1994
	Self potential profile surveys, tot. 3 km ²	GTK		1980s–2000s
	VLF-R profile surveys, tot. 201 km ²	GTK		1970s–1980s
	Slingram, VLF, radiometric, magnetic surveys	Rautaruukki		1970s
	Slingram regional survey, tot. 32 km ²	Outokumpu		1970s–1980s
	IP regional survey, tot. 20 km ²	Outokumpu		1970s–1980s
Drilling	Gravimetric survey, regional, systematic, total 79 km ²	Outokumpu		1970s–1980s
	Magnetic surveys, tot. 155 km ²	Outokumpu		1970s–1980s
	Electromagnetic, magnetic and IP surveys	Inmet Mining		2006–2009
	Radiometric survey	AREVA		2007–2009
	Magnetic, slingram, IP surveys	Mawson		2012–
	665 DDH, tot. 39,513 m	Partly yes	GTK	1940s–2010s
	4 DDH, tot. 10,185 m	Partly yes	Outokumpu	1960s–1980s
	Diamond drilling	Not known	Rautaruukki	1970s
	436 DDH, 24,443 m; reanalysis of historic core; ongoing work	Partly yes	Mawson	2010–

DDH – diamond drill hole; GTK – Geological Survey of Finland

Generalized Lithology 1M**Palaeoproterozoic**

- Quartz-feldspar gneiss
- Diorite, gabbro, peridotite, anorthosite
- Granite
- Paraschist
- Volcanic rocks, dominantly mafic composition
- Carbonate rock
- Quartzite
- Volcanic rocks, dominantly felsic composition
- Layered mafic intrusions

Archaean

- Granite and related rocks
- Gabbro, diorite
- Paraschist and -gneiss
- Volcanic rocks, dominantly mafic composition
- Volcanic rocks, dominantly felsic composition
- TTG gneiss and migmatite

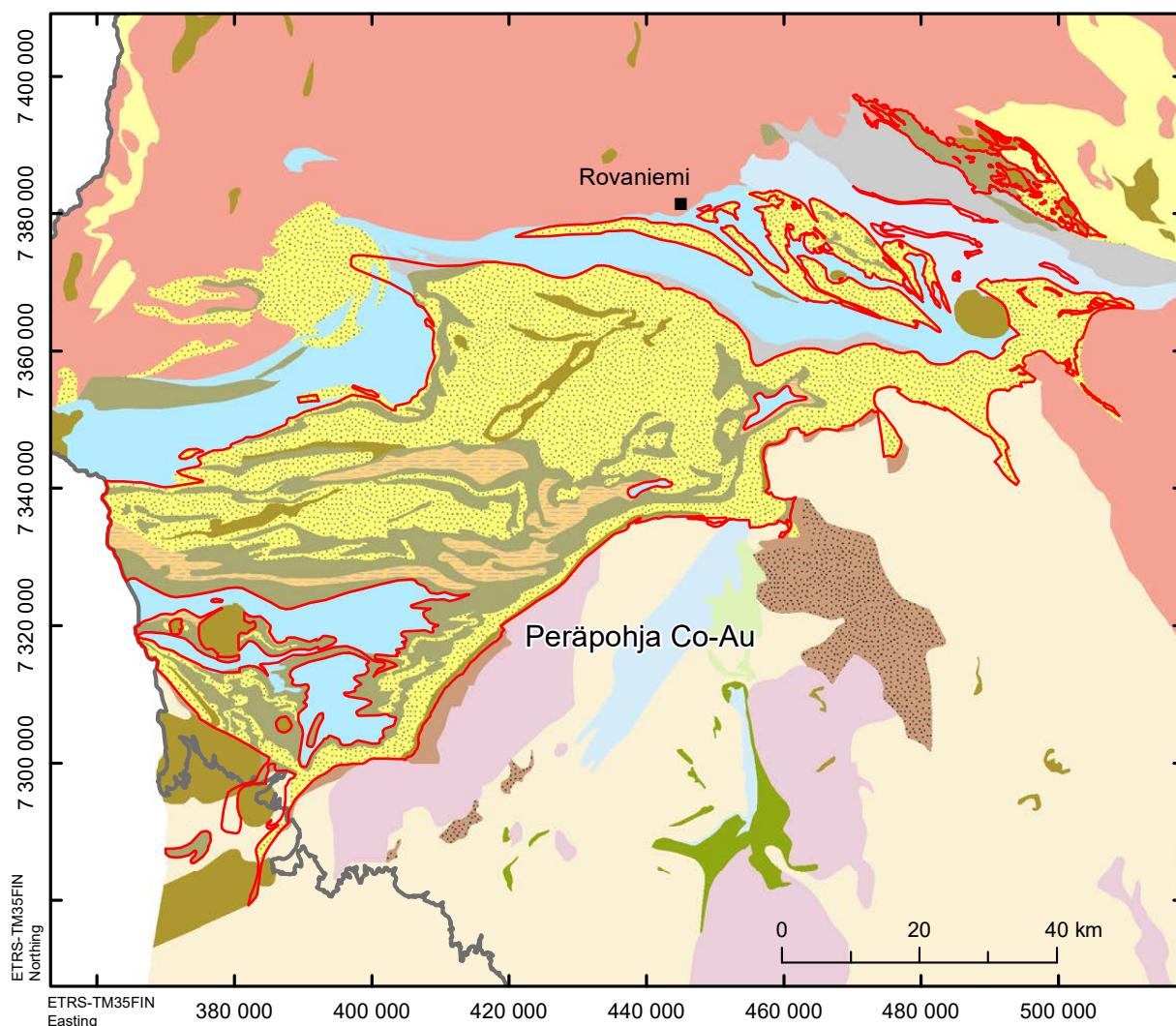
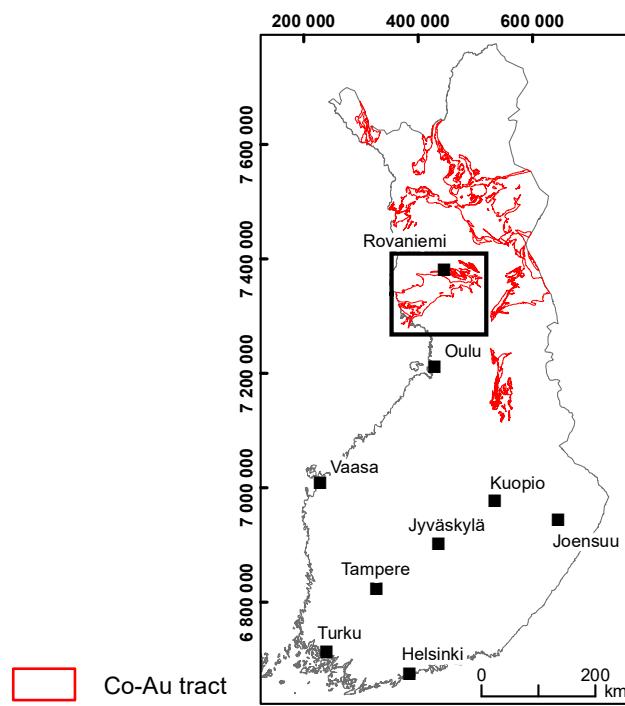


Fig. 1. Location of the Peräpohja Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Peräpohja Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Peräpohja Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database		Bedrock of Finland – DigiKP, http://gtkdata GTK.fi/Kalliopea/index.html
	Geological maps	1:100,000	Perttunen (1971a,b,c, 1975, 1991, 2002, 2003, 2005a,b), Perttunen et al. (1995), Väänänen et al. (1997), Hanski (2002, 2003), Perttunen & Hanski (2003)
	Reports and publications	1:5,000–10,000	Liipo & Laajoki (1991), Rossi (2000, 2001), Hanski et al. (2005), Isomaa & Sandgren (2006), Karvinen et al. (2007), Karvinen & Turunen (2007), Kyläkoski (2007), Turunen (2007), Pietilä (2010), Kyläkoski et al. (2012a,b), Ranta (2012), Kinnunen (2013), Vanhanen (2013), Ranta et al. (2015, 2016, 2018), Kiviniitty (2016), Nieminen (2016), Molnar et al. (2016b, 2017), Piippo et al. (2019), Skyttä et al. (2019)
Mineral occurrences	GTK gold deposit database		Eilu & Pankka (2010)
	GTK in-house database		http://gtkdata GTK.fi/mdae
	Deposit descriptions		Stigzelius & Ervamaa (1962), Aulanko (1968), Rouhunkoski (1969), Rouhunkoski & Isokangas (1974), Koivisto (1984), Äyräs (1987a,b, 1991), Lehtinen & Eilu (1987), Liipo & Laajoki (1991), Rossi (1993, 1998, 2000), Sarala (1995), Sarala & Rossi (1998), Niiranen et al. (2003), Eilu et al. (2007, 2015), Hulkki & Turunen (2008), Kyläkoski et al. (2012), Vanhanen (2013), Vanhanen et al. (2015), Ranta et al. (2018), Webster & Forrester (2018)
Geochemistry	GTK in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Wennervirta (1966), Koivisto (1984), Eilu (1987), Äyräs (1988, 1991), Nurmi et al. (1991), Sarala et al. (1999, 2007), Pulkkinen (2000), Sarala (2005, 2010), Isomaa et al. (2008), Peltoniemi-Taivalkoski (2009), Lehmuspelto & Pohjola (2010), Mustonen (2012), Molnár et al. (2016a), Niemelä (2017), Ranta et al. (2016)
Geophysics	GTK in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Rossi (2000, 2001), Isomaa & Sandgren (2006), Isomaa et al. (2007, 2008), Karvinen et al. (2007), Karvinen & Turunen (2007), Vanhanen (2013), Vanhanen et al. (2015)
Exploration	Reports		Rossi (2000, 2001), Isomaa (2004), Sarala (2005), Isomaa & Sandgren (2006), Kyläkoski (2007), Isomaa et al. (2008), Sarala & Rossi (2006), Sarala et al. (2007), Lahtinen & Lahtinen (2012), Huovinen (2013), Vanhanen (2013), Vanhanen et al. (2015)
	GTK in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

No Kuusamo-type deposits or occurrences are known from the Peräpohja tract, but several other types of occurrences have been discovered (see the section on prospects, mineral occurrences and related deposit types above). The Au±Co, U occurrences in the Rompas–Rajapalot area have some features resembling the Kuusamo type, but they are considered a separate class of deposits here. Their existence indicates that mineralising processes including cobalt have been active in the area. The

tract is large, the geology is roughly similar as in the Kuusamo area, and exploration coverage is rather poor in many areas. Nevertheless, it is not certain that Kuusamo-type mineralising processes have been active here. No consensus on the number of undiscovered deposits was reached in the discussion. The mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Peräpohja Co-Au permissive tract.

Mean undiscovered deposit estimate						Summary statistics			Area (km ²)	Deposit density (N/km ²)
N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁	N _{und}	S	Cv%	N _{known}	N _{total}	
4	9	24			12	7.4	63	0	12	4,634 0.0026

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	1	5	30		
Individual 2	4	10	20		
Individual 3	10	20	40		
Individual 4	2	5	15		
Individual 5	2	5	15		
Individual 6	2	8	25		
Mean	4	9	24		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and the total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Peräpohja Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	1,100	3,100	22,000	59,000	71,000	28,000	0.42	0.02
Au (t)	2.0	4.0	18	46	55	22	0.42	0.02
Rock (Mt)	1.2	3.1	17	43	50	21	0.42	0.02

Mt – million metric tons; t – metric ton

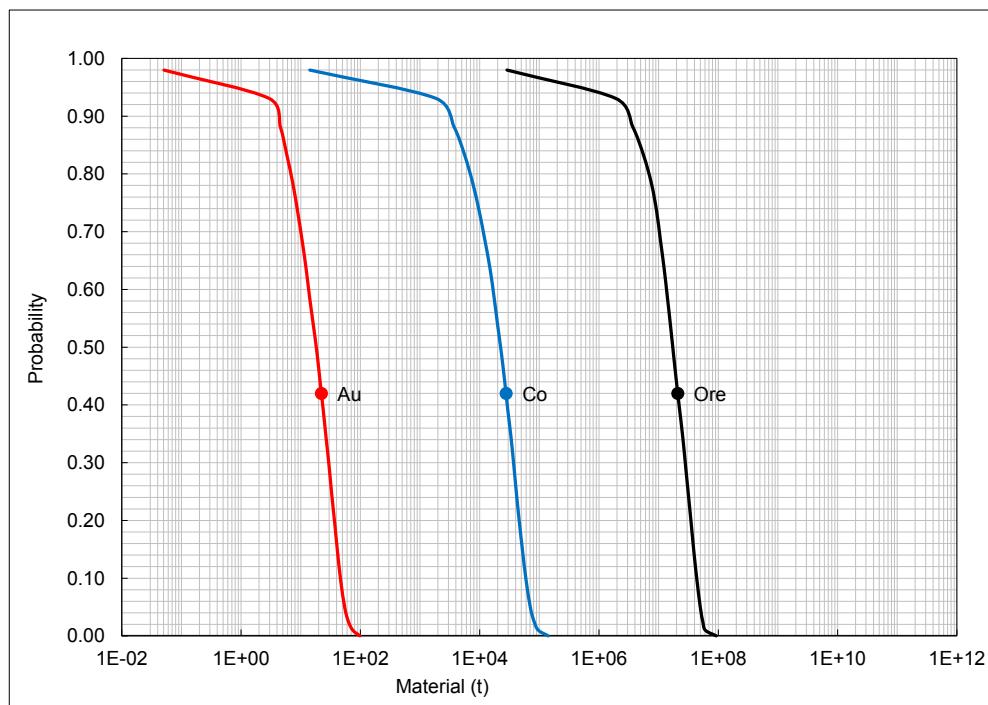


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Peräpohja Co-Au permissive tract. Labelled dots indicate mean values.

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Co ASSESSMENT FOR THE TRACT PULJU Co-Au, FINLAND

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DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Pulju Co-Au permissive tract is located in northern Finland, in the municipalities of Kittilä, Enontekiö and Inari, about 200 km north of Rovaniemi (Fig. 1). The 1:100,000 KKJ map sheets containing the tract are 2742, 2831, 2832, 2833 and

2834. The 1:50,000 UTM map sheets are V413, V414, V432, V441 and V442. The Co-Au resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Pulju Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
14/08/2018	1	790	Co 0 Au 0	Co 5,200 Au 4.1	Co 1,700 Au 2.4

t – metric ton

DELINeATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of the 2.3–2.0 Ga supracrustal sequence of Sodankylä and Savukoski Group rocks. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic groups were excluded from the tract. The tract is bounded by Archean TTG rocks in the west and south, c. 2.05 Ga Kittilä Suite

rocks in the east and the Finnish-Norwegian border in the north. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-known Kuusamo-type Co-Au deposits within the Pulju Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Pulju Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Content of metal (t)	Reference
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Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No Kuusamo-type Co-Au occurrences are known within the tract (Table 3). At least nine komatiite-related Ni-Cu occurrences, some of them rather modest, are known in the southern part of the tract, as well as two Mo showings.

Table 3. Significant Kuusamo-type Co-Au occurrences in the Pulju Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
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Ma – million years

Exploration history

Exploration within the tract has focused on Ni-Cu and Mo deposits. No gold nor Au-Co occurrences are

known from the tract. Exploration activities for the Pulju Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Pulju Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observations and boulder survey	Partly yes	GTK	1999–2007
	Outcrop observations	Partly yes	University of Turku	1970s
	Outcrop observations and boulder survey	Yes	Outokumpu Oy	1973–1997
Geochemical surveys	Nationwide till survey	Yes	GTK	1980s
	Local and regional till sampling 7820 points		Outokumpu Oy	1977–1991, 1997–1998
Airborne geophysical surveys	High-resolution, low-altitude airborne magnetic, electromagnetic and radiometric surveys		GTK	1978, 1979, 1990
	Low-altitude airborne magnetic and electromagnetic survey, 950 km ²		Outokumpu Oy	1976
Ground geophysical surveys	Local and regional magnetic surveys, 238 km ² ; slingram surveys, 245 km ² ; gravimetric surveys, 4.2 km ² ; a few IP and charge potential lines		Outokumpu Oy	1977–1991, 1997–1998
	Local magnetic and slingram survey, 28.4 line km		Anglo American	2004–2008
Drilling	4 DDH, 208.9 m		Turku Univ.	1974–1975
	65 DDH, 9504.25 m		Outokumpu Oy	1978–1991
	28 DDH, 4104.85 m		Outokumpu Oy	1997–1998
	4 DDH, 289.3 m	Yes	Anglo American	2004–2008

DDH – diamond drill hole; GTK – Geological Survey of Finland

Generalized Lithology 1M**Palaeoproterozoic**

-  Granite (1.77 Ga)
-  Quartz-feldspar gneiss
-  Diorite, gabbro, peridotite, anorthosite
-  Granodiorite, quartz diorite
-  Granite (1.83–1.79 Ga)
-  Lapland granulite belt
-  Paragneiss
-  Volcanic rocks, dominantly mafic composition
-  Quartzite
-  Volcanic rocks, dominantly felsic composition

Archaean

-  Granite and related rocks
-  TTG gneiss and migmatite

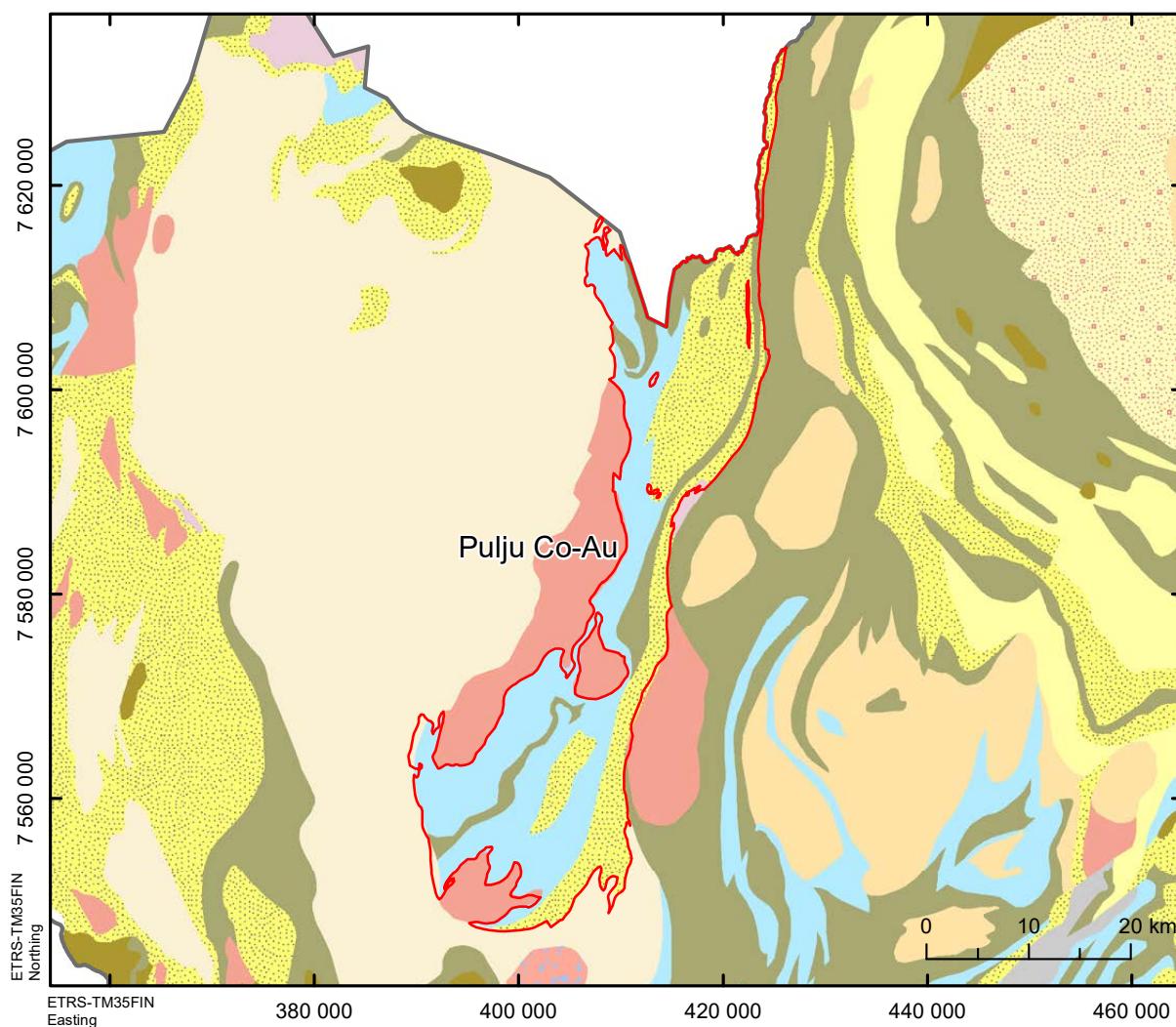
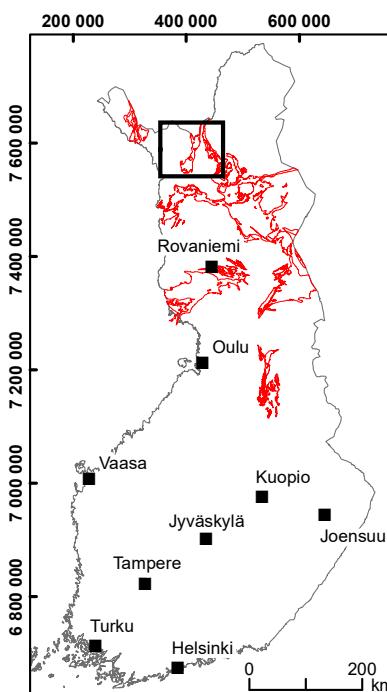
 Co-Au tract


Fig. 1. Location of the Pulju Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Pulju Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Pulju Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP, http://gtkdata GTK.fi/Kalliopera/index.html
	Reports and publications		Papunen et al. (1976), Heikkilä (1984), Johansson & Nenonen (1991), Rastas & Kilpeläinen (1991), Lehtonen et al. (1998), Papunen (1998), Ihlen (2012)
Mineral occurrences	Geological Survey of Finland in-house database		http://gtkdata GTK.fi/mdae
	Reports		Lahtinen (1979, 1980, 1992, 1998a,b), Inkinen (1982, 1987, 1988), Inkinen et al. (1984), Anttonen (1993), Meriläinen (1993)
Geochemistry	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports and publications		Kokkola (1975, 1976), Inkinen et al. (1984), Vihreäpuu (2001a,b,c), Austen (2008)
Geophysics	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Rekola (1979), Inkinen (1982), Inkinen et al. (1984), Lahtinen (1992), Vihreäpuu (2001a,b,c), Austen (2008)
Exploration	Reports		Inkinen (1976, 1978, 1982, 1985, 1987, 1988), Rekola (1979), Heikkilä (1984), Inkinen et al. (1984), Lahtinen (1979a,b,c, 1992), Vihreäpuu (2001a,b,c), Austen (2008)
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

Very little information is available for the tract. No indications for Kuusamo-type Co-Au mineralisation are known, although other types of mineral occurrences exist within the tract. Exploration has been limited, especially in the northern part of the tract. In a northern continuation of the tract into Norway, there is a sequence of rocks indicating a

shallow water depositional environment and possibly including evaporates (Sandstad 2012, Melezhik et al. 2015). Consensus on the number of undiscovered deposits was not reached in the discussion. The mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Pulju Co-Au permissive tract.

Mean undiscovered deposit estimate Summary statistics						Area (km ²)	Deposit density (N/km ²)				
N90	N50	N10	N05	N01	N _{und}	S	Cv%	N _{known}	N _{total}		
0	2	5			2.3	1.8	80	0	2.3	790	0.0029

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	0	0	5		
Individual 2	0	4	6		
Individual 3	0	2	4		
Individual 4	0	0	5		
Individual 5	0	1	2		
Individual 6	0	4	8		
Individual 7	0	2	5		
Mean	0	2	5		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Juhani Ojala, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and the total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Pulju Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	0	0	1,700	16,000	22,000	5,200	0.32	0.21
Au (t)	0	0	2.4	11	15	4.1	0.34	0.21
Rock (Mt)	0	0	1.6	10	14	3.9	0.37	0.21

Mt – million metric tons; t – metric ton

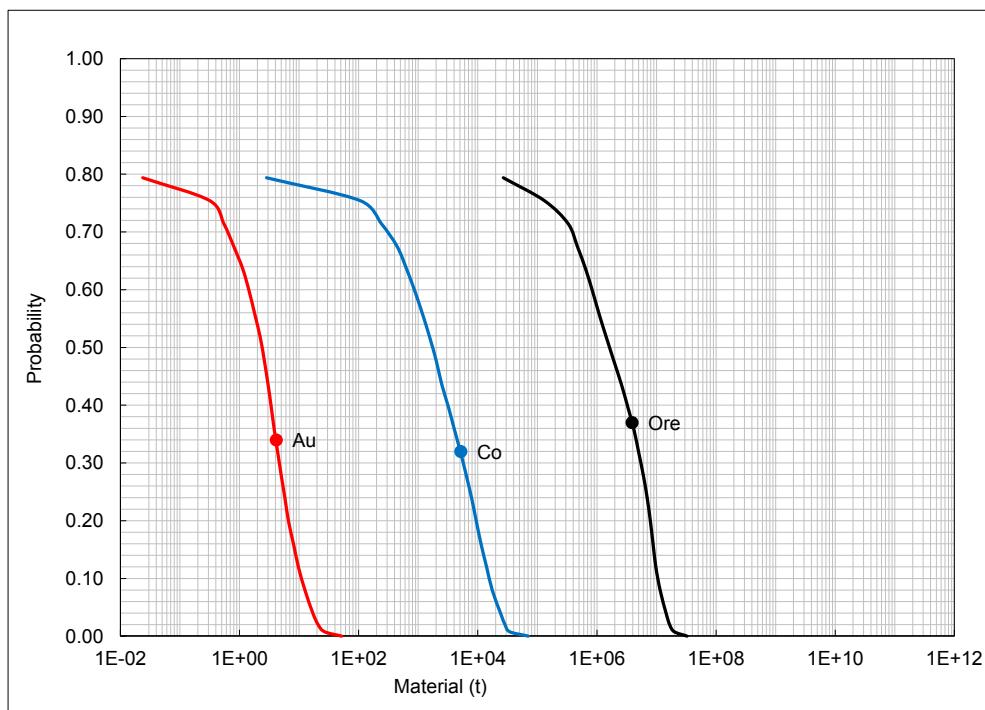


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Pulju Co-Au permissive tract. Labelled dots indicate mean values.

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Co ASSESSMENT FOR THE TRACT SODANKYLÄ Co-Au, FINLAND

Törmänen, T. & Eilu, P.

Geological Survey of Finland, P.O. Box 77, FI-96101 Rovaniemi

DEPOSIT TYPE ASSESSED

Deposit type: Kuusamo-type Co-Au

Descriptive model: Kuusamo-type Co-Au (Appendix 1)

Grade-tonnage model: Kuusamo-type Co-Au (Appendix 2)

LOCATION AND RESOURCE SUMMARY

The Sodankylä Co-Au permissive tract is located in northern Finland, in the municipalities of Sodankylä, Kittilä, Savukoski and Inari (Fig. 1). The 1:100,000 KKJ map sheets containing the tract are 2833, 2834, 3712, 3714, 3721, 3722, 3723, 3724, 3732, 3741, 3743, 3744, 3811, 4721, 4722 and 4724.

The 1:50,000 UTM map sheets are U443, U444, U521, U522, V431, V432, V433, V434, V441, V442, V443, V511, V514, V514, V531 and W431. The Co-Au resource assessment carried out for this report is summarised in Table 1.

Table 1. Summary of selected resource assessment results for the Sodankylä Co-Au permissive tract.

Date of assessment	Assessment depth (km)	Tract area (km ²)	Known metal resources (t)	Mean estimate of undiscovered resources (t)	Median estimate of undiscovered resources (t)
14/08/2018	1	3,228	Co 0 Au 0	Co 13,000 Au 10	Co 8,900 Au 7.7

t – metric ton

DELINEATION OF THE PERMISSIVE TRACT

Geological criteria

The permissive tract is defined by the known extent of the 2.44–2.0 Ga supracrustal sequence of Kuusamo, Sodankylä and Savukoski Group rocks in north-east Lapland. Areas of rock inside tract boundaries but not belonging to the aforementioned lithologic groups were excluded from the tract. The tract is bounded in the west by the c. 2.05 Ga Kittilä Suite and the north-east boundary is defined by the contact between the Kola and Karelian provinces. The southern boundary to the

adjacent Pelkosenniemi tract is defined by gradient change in the peak metamorphic degree from mid-greenschist facies in the north to mid-amphibolite facies in the south. The tract extends down to 1000 m depth. The depth extension is based on the assumption that the geology is largely similar downwards as at the present erosion level. The sources of information used in the delineation of the tract are summarised in Table 5.

Known deposits

There are no well-known Kuusamo-type Co-Au deposits within the Sodankylä Co-Au permissive tract (Table 2).

Table 2. Known Kuusamo-type Co-Au deposits in the Sodankylä Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ga)	Tonnage (Mt)	Metal grade	Contained metal (t)	Reference
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Ma – million years; Mt – million metric tons; t – metric ton

Prospects, mineral occurrences and related deposit types

No Kuusamo-type Co-Au occurrences are known within the tract (Table 3). There are three orogenic Au occurrences and one producer in care and maintenance (Pahtavaara) within the tract. The Sakatti Ni-Cu-PGE deposit, Lomalampi PGE-Ni-Cu prospect, four Ni occurrences and one Cu occurrence are

also with the tract. Of the Au and Cu occurrences, the Kirakka-aapa Au occurrence contains elevated cobalt contents (up to 1500 ppm) and the Maaselkä Cu occurrence contains some cobalt (up to 1500 ppm, but possibly not systematically analysed).

Table 3. Significant Kuusamo-type Co-Au occurrences in the Sodankylä Co-Au permissive tract.

Name	Easting EUREF	Northing EUREF	Age (Ma)	Comments	Reference
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Ma – million years

Exploration history

Exploration activities for the Sodankylä Co-Au tract are listed in Table 4.

Table 4. Exploration history for the Sodankylä Co-Au permissive tract.

Theme	Type of work	Co analysed	Organisation	When carried out
Mapping	Outcrop observation and boulder survey	Yes	GTK	1960s–present
	Outcrop observation and boulder survey	Yes	Outokumpu Oyj	1960s–2000s
	Outcrop observation and boulder survey	Yes	Anglo American	2004–present
	Outcrop observation and boulder survey	Yes?	FQM FinnEx	2011–2015
Geochemical surveys	Nationwide till survey, 709 samples	Yes	GTK	1971–1991
	Targeting till geochemistry, 30976 samples	Yes	GTK	1972–1981
	Line till geochemistry, 2455 samples	Partially yes	Outokumpu Oyj	1970s–2000s
	MMI, 112 samples	Yes	GTK	2007–2008
	Base of till sampling, 3006 samples; surface soil sampling, 263 samples		Anglo American	2010–2017
Airborne geophysical surveys	Base of till sampling, 5000 samples	Yes	FQM FinnEx	2011–2015
	High-resolution, low-altitude airborne magnetic, electromagnetic and radiometric surveys		GTK	1975–79, 1981, 1987, 1990, 1992–94, 1999, 2000–01, 2004,
	High-resolution airborne EM, magnetic, gravity surveys		Anglo American	2010–2014
Ground geophysical surveys	Systematic gravity surveys, 105 km ²		GTK	1984–2012
	Systematic magnetic survey, 275 km ²		GTK	1970–2012
	Systematic slingram survey, 170 km ²		GTK	1970–1987
	Systematic IP survey, 2.5 km ²		GTK	2001–2007
	Systematic VLF/VLF-R survey, 100 km ²		GTK	1984–2007
	Systematic magnetic survey, 10 km ²		Outokumpu Oyj	1970s–1990s
	Systematic slingram survey, 10 km ²		Outokumpu Oyj	1970s–1990s
	EM survey, 6.15 line km		BHP Billiton	2004
	Magnetic surveys		RTZ Mining and Exploration	2004
	EM and magnetic surveys, 152 line km		Anglo American	2014–2017
Drilling	Systematic EM and magnetic surveys		FQM FinnEx	2011–2015
	21 DDH, 436m	Yes?	Suomen Malmi Oy	1966–1967
	41 DDH, 5518m	Yes?	Outokumpu Oy	1962–1998
	19 DDH, 400 m	No	Kemijoki Oy	1974
	5 DDH, 2004 m	Yes	University of Turku	1978
	1048 DDH, 59897 m	Yes	GTK	1979–2012
	3 DDH, 131.15 m	No?	RTZ Mining and Exploration	1994–1995
	43 DDH, 11659 m	Yes	Anglo American	2005–2015
	55 DDH	Yes	FQM FinnEx	2011–2015

DDH – diamond drill hole, GTK – Geological Survey of Finland

Generalized Lithology 1M**Palaeozoic**

Devonian alkaline rock

Palaeoproterozoic

- Granite (1.77 Ga)
- Paragneiss
- Quartz-feldspar gneiss
- Diorite, gabbro, peridotite, anorthosite
- Granodiorite, quartz diorite
- Granite (2.1–1.79 Ga)
- Lapland granulite belt
- Serpentinite, ophiolites
- Parachist
- Volcanic rocks, dominantly mafic composition
- Quartzite
- Volcanic rocks, dominantly felsic composition
- Layered mafic intrusions

Archaean

- Granite and related rocks
- Parachist and -gneiss
- Volcanic rocks, dominantly mafic composition
- TTG gneiss and migmatite

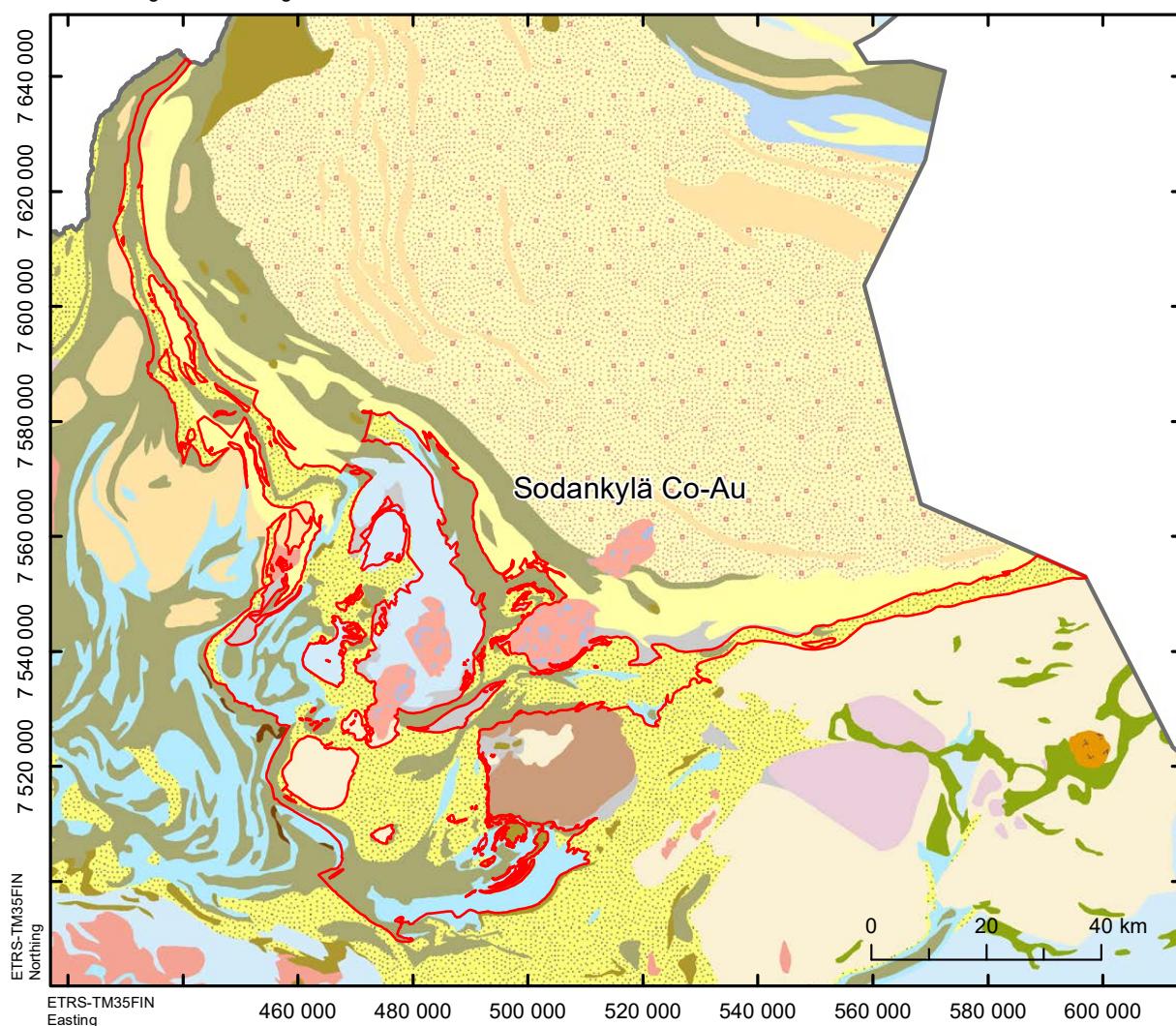
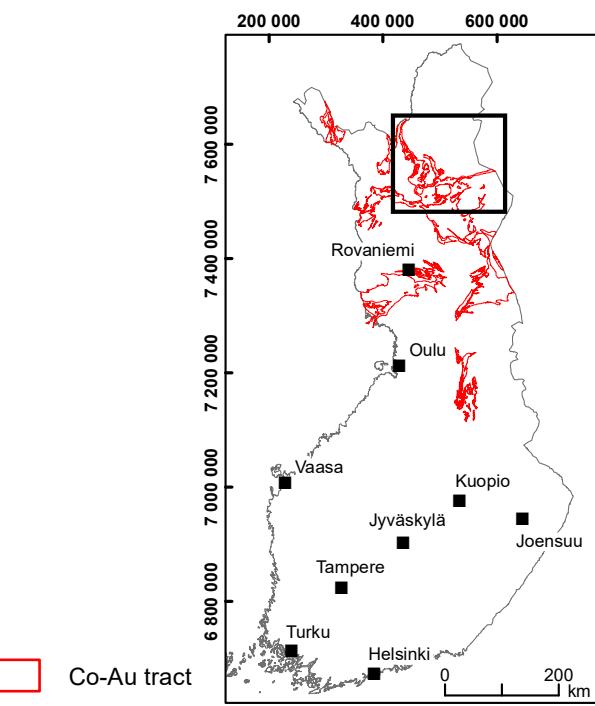


Fig. 1. Location of the Sodankylä Co-Au permissive tract.

Sources of information

Principal sources of information used by the assessment team for the delineation of the Kuusamo Co-Au tract are listed in Table 5.

Table 5. Principal sources of information used by the assessment team for the Sodankylä Co-Au permissive tract.

Theme	Type of source	Scale	Reference
Geology	Bedrock Map Database DigiKP Finland		Bedrock of Finland – DigiKP
	Reports and publications		Lehtonen et al. (1998), Räsänen (2005), Hölttä et al. (2007)
Mineral occurrences	Geological Survey of Finland in-house database		http://gtkdata GTK.fi/mdae
	Reports		Korkiakoski (1992), Rossi (1983, 1991), Pulkkinen & Rossi (1984), Keinänen et al. (2007), Pulkkinen et al. (2001, 2007, 2008), Törmänen et al. (2010)
Geochemistry	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports and publications		Lehmuspelto & Vuojärvi (1979), Lestinen (1980), Pulkkinen & Rossi (1984), Pulkkinen et al. (1991), Salminen (1995), Sarala et al. (2008)
Geophysics	Geological Survey of Finland in-house database		https://hakku GTK.fi/en/locations/search
	Reports		Airo (1990), Turunen (2004), Thuned & Pitkänen (2006), Pulkkinen et al. (2007)
Exploration	Reports		Isomaa (1998), Sims (1996a,b,c), Alitalo (2005a,b,c), FQM FinnEx (2016a,b,c,d), Mikkola & Reynolds (2016a,b, 2017a,b,c)
	National drill core archive, Loppi		https://www GTK.fi/en/research-infrastructure/national-drill-core-archive/
	Geological Survey of Finland in-house drill-core database		https://hakku GTK.fi/en/locations/search

ESTIMATE OF THE NUMBER OF UNDISCOVERED DEPOSITS

Rationale for the estimate

No Kuusamo-type mineral occurrences are known within the tract. The other types of mineral occurrences known in the area indicate that gold, copper and also cobalt have been mobilised by mineralising processes. Source rocks for cobalt exist within the tract, and the existence of evaporates is likely according to geological analogy to other areas. The geologically strongest potential (central) area has been explored, but no Kuusamo-type deposits

have been discovered – unless Kirakka-aapa and Maaselkä are such. However, the tract is large, and the northern and eastern extensions are less well known and explored. Consensus on the number of undiscovered deposits was not reached in the discussion. The mean values of the numbers given by the individual estimators were used as input to Eminers software (Table 6).

Table 6. Undiscovered deposit estimates, deposit numbers, tract area and deposit density for the Sodankylä Co-Au permissive tract.

Mean undiscovered deposit estimate Summary statistics						Area (km ²)	Deposit density (N/km ²)			
N90	N50	N10	N05	N01	N _{und}	S	Cv%	N _{known}	N _{total}	
1	5	11			5.5	3.6	65	0	5.5	3,228 0.0017

Estimated number of undiscovered deposits					
Estimator	N ₉₀	N ₅₀	N ₁₀	N ₀₅	N ₀₁
Individual 1	1	5	10		
Individual 2	0	6	10		
Individual 3	2	4	8		
Individual 4	1	2	8		
Individual 5	1	5	10		
Individual 6	2	9	17		
Individual 7	1	6	15		
Mean	1	5	11		

N_{xx} – Estimated number of deposits associated with the xxth percentile; N_{und} – expected number of undiscovered deposits; s – standard deviation; Cv% – coefficient of variance; N_{known} – number of known deposits in the tract that are included in the grade-tonnage model; N_{total} – total of expected number of deposits plus known deposits; Area – area of permissive tract; Deposit density – deposit density reported as the total number of deposits per km². N_{und}, s, and Cv% are calculated using a regression equation (Singer & Menzie 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed. Estimators (not in the order of the list above): Pasi Eilu, Irmeli Huovinen, Jukka Konnunaho, Tero Niiranen, Juhani Ojala, Kalevi Rasilainen, Tuomo Törmänen.

QUANTITATIVE ASSESSMENT SIMULATION RESULTS

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the Kuusamo-type Co-Au grade-tonnage model (Appendix 2) using Eminers software (Root et al. 1991, Duval 2012). Results of the Monte Carlo simulation are presented as cumulative frequency

plots (Fig. 2) and selected simulation results are reported in Table 7. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for cobalt, gold and the total mineralised rock.

Table 7. Results of Monte Carlo simulations of undiscovered resources in the Sodankylä Co-Au permissive tract.

Material	At least the indicated amount at the probability of					Mean	Probability of mean or greater	Probability of zero
	0.95	0.90	0.50	0.10	0.05			
Co (t)	0	160	8,900	31,000	39,000	13,000	0.40	0.07
Au (t)	0	0.51	7.7	23	29	10	0.40	0.07
Rock (Mt)	0	0.23	8.1	21	26	10	0.43	0.07

Mt – million metric tons; t – metric ton

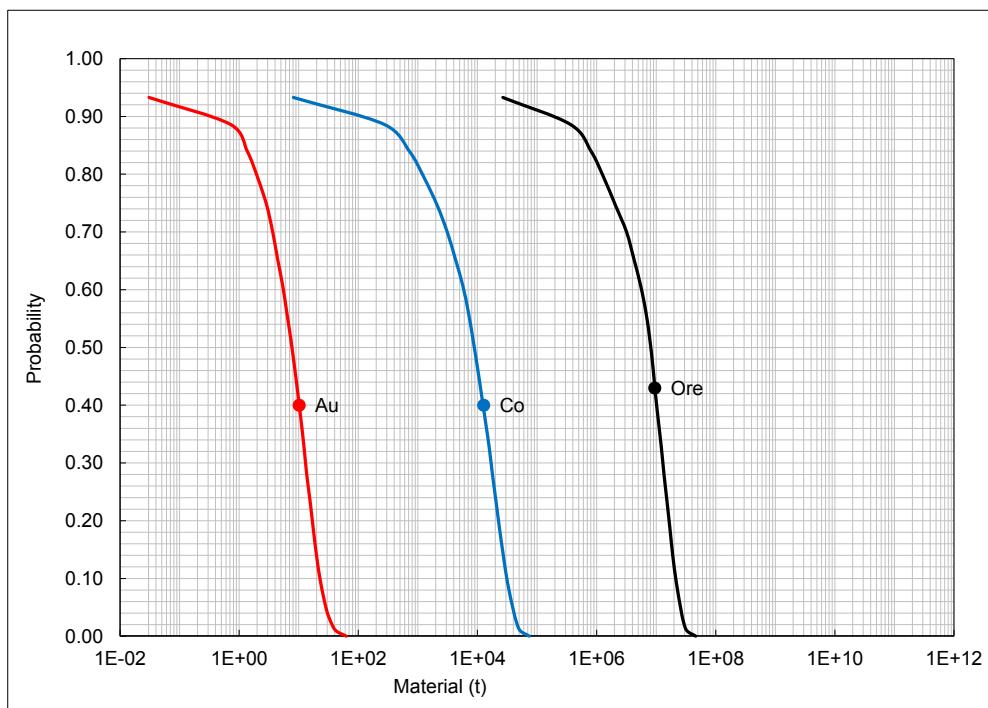


Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Sodankylä Co-Au permissive tract. Labelled dots indicate mean values.

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The present work uses statistical and expert assessment methods to estimate undiscovered resources in Kuusamo-type Co-Au deposits in the uppermost one kilometre of the bedrock in Finland. It provides numerical estimates for the expected endowment of cobalt and gold in undiscovered, but potentially exploitable, deposits in Finland.