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Assessment process for undiscovered mineral resources at GTK

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Abstract This report describes the three-part quantitative assessment method and the recommended way it should be applied in GTK assessment projects. The recommendations are based on experience acquired in the assessments of undiscovered mineral resources in Finland during 2008–2021. The report begins with an overview of the three-part method. This is followed by a description the process of carrying out an assessment using the method. Available software is listed, and directions of further development are suggested.			
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Contents

1 INTRODUCTION

The Geological Survey of Finland (GTK) conducted domestic assessments of undiscovered mineral resources during 2008–2021. The assessment method used followed the three-part quantitative assessment method (Singer 1993, Singer & Menzie 2010). The core of the method remained the same during the period, but changes and improvements were made to the process, based on experience gained from previous work. This document describes the final evolved process for quantitative assessments of undiscovered mineral resources. The document concentrates on technical aspects and tasks that must be performed and guidelines and rules that should be followed. Administrative aspects of an assessment project or organisation of the work are not considered, but it is assumed that the required personnel and other resources are available.

The document begins with an introduction to the three-part quantitative assessment method. This is followed by a description of an ideal assessment process, based on experience gained during the work in 2008–2021. Examples of documents used and produced are given, as well as recommendations for best practices. Various tools to be used in different parts of the assessment process are introduced and suggestions for future development of the assessment process and software are made.

1.1 GTK assessments

In 2007, increasing requests from various stakeholders to produce more accurate and versatile information on potential mineral resources yet to be discovered in Finland resulted at GTK in the decision to begin a program to answer these requests. During a preparation phase in 2007, available literature was studied, and visits were made to the U.S. Geological Survey (USGS) in Reston, Virginia, and the Geological Survey of Canada in Ottawa, Ontario, where the methods in use in these organisations were introduced to GTK scientists. As a result of the preparation phase, the three-part quantitative assessment method developed in the USGS was considered the most suitable solution to GTK needs. The method was in production use and the most widely applied method worldwide. 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 GTK assessment program was initiated in 2008, and it continued until the end of 2021. During that time, the quantity of undiscovered resources of the most relevant and significant commodities in the Finnish bedrock were estimated. The following deposit classes were included in the assessments: 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), Kuusamo-type cobalt-gold deposits (Rasilainen et al. 2020), orthomagmatic mafic intrusion-related iron-titanium-vanadium deposits (Halkoaho et al., *in preparation*), and carbonatite and peralkaline intrusion-related rare earth element-phosphorus deposits (Rasilainen et al. 2023). The GTK assessments were published in GTK Report of Investigation series (2010–2016) and in GTK Bulletin series (2018–2023). Links to these reports are listed in Appendix 1.

A few important deposit types potentially containing significant undiscovered resources were not quantitatively assessed due to the scarcity of well-known deposits of the types, which prevented the creation of relevant deposit models. These deposit types include Talvivaara nickel-zinc-copper-cobalt, Kevitsa nickel-copper-platinum group metal, metamorphosed epithermal gold, and iron oxide-copper-gold.

The purpose of the GTK assessments was to provide unbiased estimates of the amount of undiscovered metals within the Finnish bedrock, down to one kilometre depth. The intended uses of the assessment results included national and regional planning for land use, natural resources management and environmental planning, accounting of metallic natural resources according to the principles of sustainable development, and metallogenic and lithologic research.

2 TERMINOLOGY

Some terms essential to the proper understanding of this report are briefly described below. The definitions concerning mineral deposits, occurrences, resources, and reserves 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, CRIRSCO 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 resource

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

Well-known resource

Identified resource that occurs in completely delineated deposits included in grade-tonnage models.

Discovered resource

The sum of identified resource and cumulative past production.

Undiscovered resource

Resource in undiscovered mineral deposits whose existence is postulated based on indirect geological evidence.

Hypothetical resource

Undiscovered resource 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 resource

Undiscovered resource 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.

3 THE THREE-PART QUANTITATIVE RESOURCE ASSESSMENT METHOD

Numerous methods have been developed for and applied to the estimation of undiscovered mineral resources during the past decades. The task nevertheless remains challenging and no universally accepted, definitive procedure exists (e.g., Lisitsin et al. 2007). 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.

Development of the three-part quantitative assessment method began at the USGS in the mid-1970s and has continued through the years (Singer 1975, Cox & Singer 1986, Root et al. 1992, Harris et al. 1993, Barton et al. 1995, Singer 1993, Drew 1997, Duval

2000, 2002, 2004, 2012, Singer & Menzie 2010, Schuenemeyer et al. 2011, Ellefsen 2017, Shapiro 2018, Ross & Lederer 2021). The method 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, 2016, 2018, 2020, Mihalasky et al. 2011, 2015a,b, Stensgaard et al. 2011, Box et al. 2012, Ludington et al. 2012a,b, Rosa et al. 2013, 2014, Sørensen et al. 2013, Sutphin et al. 2013, Berger at al. 2014, Cossette et al. 2014, Gray et al. 2014, Zientek et al. 2014a,b,c, 2015a,b, Eilu et al. 2015, Kolb 2015, Zürcher et al. 2015, Wynn et al. 2016, Cocker et al. 2017, Thrane & Kalvig 2018, Thrane et al. 2018).

It must be emphasised that the three-part method does not provide mineral resource or reserve estimates consistent with the present industrial standards such as the JORC, CRIRSCO, NI 43-101 and PERC codes (JORC 2012, CRIRSCO 2013, NI 43-101 2011, PERC 2013). The results of undiscovered resource assessments should never be confused with proper reserve or resource estimates based on these international standards. Rather, the assessment process produces probabilistic estimates of the total amount of metals in situ in undiscovered deposits of selected types, down to a predefined depth. In the United Nations Framework Classification for Resources (the UNFC reporting guidelines), the undiscovered resources belong into the category E3,F4,G4 (United Nations Economic Commission for Europe 2020). The process used in the GTK assessments does not consider 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 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).

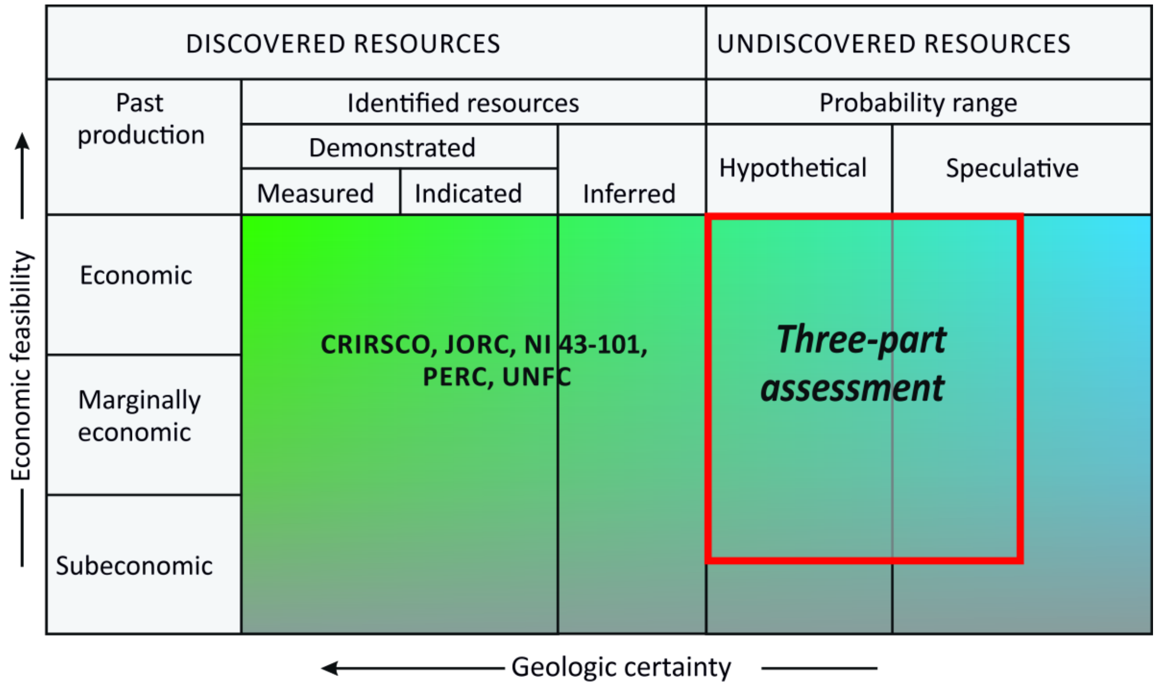

Figure 1. Classification of mineral resources used in GTK assessments. Economic feasibility increases upwards and geological uncertainty increases to the right. Modified from U.S. Geological Survey National Mineral Resource Assessment Team 2000.

The three-part assessment method is based on mineral deposit types. As different deposit types tend to have different properties, including average ore tonnages and metal grades, performing the assessment for one specific deposit type at a time reduces the variation of these properties and, hence, reduces the uncertainty of the 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. In quantitative resource analysis, the estimated number of deposits is combined with the grade and tonnage distributions from the deposit models to assess the total undiscovered metal endowment.

The parts of the method are described in the following sections. However, a deeper understanding of the complete assessment process, and the ability to run assessments using the three-part method, requires a more detailed and thorough explanation. The book by Singer and Menzie (2010) is highly recommended.

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 used in the three-part assessment method include descriptive, grade-tonnage, deposit density, and geoenvironmental models. Descriptive models and grade-tonnage models are an essential component of the three-part method and required in every assessment. Deposit density models can be used directly or as a guideline in the estimation of the number of undiscovered deposits for an area. Geoenvironmental models can be used to estimate the environmental effects of mining a deposit.

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 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.

Descriptive models prepared to be used in three-part quantitative assessments have been published by USGS. The early models were short documents listing the properties of the deposits and their surroundings, but the more recent models have evolved to documents having tens to hundreds of pages and containing detailed descriptions of all aspects of the deposits and their geological environments. A list of USGS deposit models is available at *www.usgs.gov/programs/mineral-resources-program/science/global-mineral-resource-assessments* and at *https://pubs.er.usgs.gov/.*

The descriptive models used in GTK assessments in 2008–2021 were mostly based on existing USGS models and modified according to the Finnish geological environments. The documents were generally short listings of deposit environments and properties. An example of a descriptive model used in GTK assessments is given in Appendix 2. In a few of the most recent GTK assessments, the existing USGS deposit model was used as such, and no short summary descriptive model was produced.

3.1.2 Grade-tonnage models

A grade-tonnage model is based on data of average metal grades and the associated total tonnages 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 (Fig. 2). 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 into one deposit in the grade-tonnage model.

Grade-tonnage models prepared to be used in three-part quantitative assessments have been published by USGS. A list of USGS deposit models is available at *https://www.usgs.gov/programs/mineral-resources-program/science/global-mineral-resource-assessments* and at *https://pubs.er.usgs.gov/.*

The grade-tonnage models used in GTK assessments in 2008–2021 were mostly based on existing USGS models, which were updated and modified according to the Finnish or Fennoscandian shield environments. As an example, the grade-tonnage model used in the GTK assessment of undiscovered resources associated with carbonatite- and peralkaline intrusion-related REE-P deposits is given in Appendix 3.

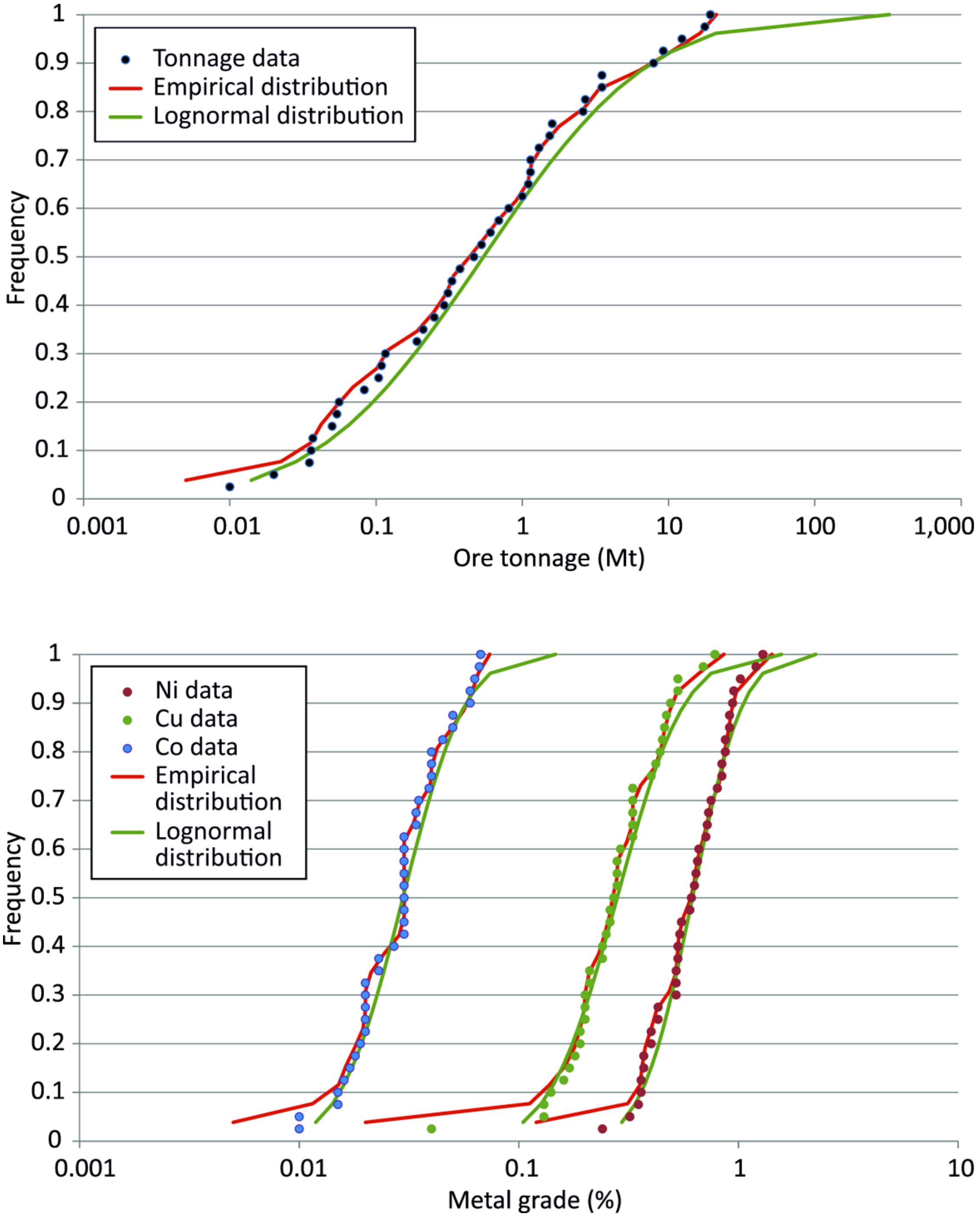

Figure 2. Frequency distributions of tonnage and average metal grades in well-known Fennoscandian synorogenic intrusion-related Ni-Cu deposits (Rasilainen et al. 2012). Original data is shown as points, and estimated distributions as lines.

3.1.3 Deposit density models

A deposit density model is based on number of deposits per unit area from several well-explored control tracts for a deposit type. The resulting frequency distribution can be used either directly or as a guideline for an estimate of the number of undiscovered deposits within a permissive tract (Singer & Menzie 2010). The deposit density model must be consistent with the grade-tonnage model and the descriptive model for the deposit type in question. Only well-explored parts of the control tracts are included in the model data. Covered areas are not included as they are typically not well explored. Mineral occurrences without a resource estimate or incompletely explored deposits are not counted in the density control tracts.

USGS has compiled deposit density data for various deposit types since the 1980s (Bliss et al. 1987, Singer et al. 2001, Singer 2008, Singer & Menzie 2010). For most deposit types covered, data exist for only a limited number of control tracts, but for porphyry copper, volcanogenic massive sulphide and podiform chromite deposit types, there are sufficient data for a regression model of deposit density against tract area to be constructed (Singer 2008, Singer & Menzie 2010). A general deposit density model including 10 deposit types from 109 control tracts uses regression of density of deposits against median tonnages of deposits and areas of control tracts (Singer 2008, Singer & Kouda 2011).

Deposit density models were used as guidelines in part of the GTK assessments. Deposit calculators based on the deposit-specific and general deposit density models are given in the Electronic supplement to this report.

3.1.4 Geoenvironmental models

A geoenvironmental model is a natural extension of a descriptive model and contains geologic, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behaviour of geologically similar mineral deposits prior to mining, and resulting from mining, mineral processing, and smelting (Plumlee & Nash 1995). A geoenvironmental model provides information about natural geochemical variations associated with a particular deposit type, and geochemical variations associated with its mining effluents, wastes, and mineral processing facilities, including smelters. Geoenvironmental models can be used in environmental prediction and mitigation, baseline characterization, grass-roots mineral exploration, and assessment of abandoned mine lands and mine-site remediation.

USGS has developed geoenvironmental models since the 1990s (du Bray 1995, Seal & Foley 2002). Geoenvironmental models were not used in GTK assessments, and to our knowledge, there are no published literature of their use in any quantitative assessment using the three-part method.

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 in fact 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 is 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.

When possible, tract delineation tasks in the GTK assessments were assigned to those assessment team members who were most familiar with the geology of the area in question. After the borders of a tract were defined, the delineation criteria as well as available geological, geochemical, geophysical and exploration information were compiled into a preliminary tract report (Appendix 4).

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 normally given at three probability levels: 10 %, 50 %, and 90 %. The number of deposits N estimated at X % probability level indicates the largest number of deposits present with probability of X % or more; the probability of more than N deposits is less than X %. The estimates can additionally be made at 5 % and 1 % probability levels, but these should only be used in cases where the estimates at 10 % and 50 % probability levels are one or zero. Uncertainty of the estimate is indicated by the spread between the numbers associated with the 90 % and 10 % probability levels. The expected number of undiscovered deposits at a given probability level can be taken as a measure of the favourability of the existence of the deposit type.

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 deposit density models showing the frequency of deposits in well-explored geologically analogous areas (Singer et al. 2001, Singer 2008, Singer & Kouda 2011), 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 number-of-deposits estimates are typically made by a team of experts knowledgeable about the deposit type and the geology of the region. A typical estimation process begins with a round of independent estimates by the experts. The results of the first estimation round are brought into general discussion, and the experts can modify their estimates based on information received during the discussion. The process can be continued until a consensus estimate is reached, or the mean or median values of the experts' estimates can be used as the final estimate.

In all the GTK assessments, the number of undiscovered deposits was estimated for each permissive tract in an assessment workshop or series of workshops. Consensus was not forced, and consequently not always reached, in which case median values of the estimators' numbers were selected to represent the final estimate.

3.4 Quantitative resource analysis

3.4.1 Monte Carlo simulation

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 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, Ross & Lederer 2021). The simulations are carried out separately for each permissive tract and for combinations of tracts as required, and they produce probability distributions of the estimated amount of undiscovered resources of each commodity (Table 1, Fig. 3).

Eminers software (Duval 2012) was used in all GTK assessments. The software estimates a non-parametric empirical distribution and a lognormal distribution for the commodity grades and ore tonnages in the grade-tonnage model dataset, and a non-parametric empirical distribution for the numbers of undiscovered deposits within the permissive tracts. It then repeatedly samples these distributions to calculate the probability distributions of commodity tonnages in the simulated undiscovered deposits. A nonparametric empirical distribution was used for the ore tonnage and commodity grades in all GTK assessments. The Eminers grade-tonnage models used in the GTK assessments are included in the Electronic supplement to this report.

Table 1. Monte Carlo simulation results for various types of VMS deposits in Finland. Based on Rasilainen et al. (2014).

VMS felsic	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
Cu (t)	1,200	11,000	160,000	1,300,000	2,500,000	580,000	0.21	0.04
Zn (t)	7,000	59,000	1,100,000	11,000,000	19,000,000	4,100,000	0.22	0.04
Pb (t)	550	5,200	140,000	1,800,000	3,700,000	1,000,000	0.16	0.04
Au (t)	0.087	0.67	13	120	220	55	0.19	0.04
Ag (t)	4.5	47	900	9,400	18,000	4,100	0.20	0.04
Ore (Mt)	0.29	2.4	31	310	500	100	0.25	0.04

VMS bimodal-mafic	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
Cu (t)	2,000	11,000	120,000	470,000	640,000	190,000	0.35	0.04
Zn (t)	4,300	22,000	230,000	990,000	1,400,000	400,000	0.34	0.04
Pb (t)	29	200	4,300	55,000	93,000	20,000	0.23	0.04
Au (t)	0.057	0.27	2.2	7.3	9.5	3.1	0.37	0.04
Ag (t)	0.63	3.3	38	250	430	100	0.25	0.04
Ore (Mt)	0.22	1.0	10	38	49	16	0.37	0.04

VMS mafic	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
Cu (t)	0	13,000	450,000	4,700,000	7,900,000	1,800,000	0.24	0.06
Zn (t)	0	6,100	260,000	3,200,000	5,900,000	1,300,000	0.22	0.06
Pb (t)	0	29	2,900	77,000	200,000	47,000	0.14	0.06
Au (t)	0	0.028	1.6	20	42	9.4	0.19	0.06
Ag (t)	0	3.8	170	1,900	3,500	750	0.23	0.06
Ore (Mt)	0	0.90	35	400	640	130	0.27	0.06

VMS all	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
Cu (t)	4,200	35,000	730,000	6,400,000	11,000,000	2,500,000	0.24	0.04
Zn (t)	14,000	88,000	1,600,000	15,000,000	27,000,000	5,800,000	0.22	0.04
Pb (t)	750	6,000	150,000	1,900,000	4,000,000	1,000,000	0.16	0.04
Au (t)	0.19	1.1	16	150	280	68	0.20	0.04
Ag (t)	8.0	56	1,100	12,000	23,000	5,000	0.20	0.04
Ore (Mt)	0.65	4.4	76	750	1,200	250	0.26	0.04

Ore: Mineralised rock containing the metals. The estimated amounts of metal and ore are rounded to two significant digits.

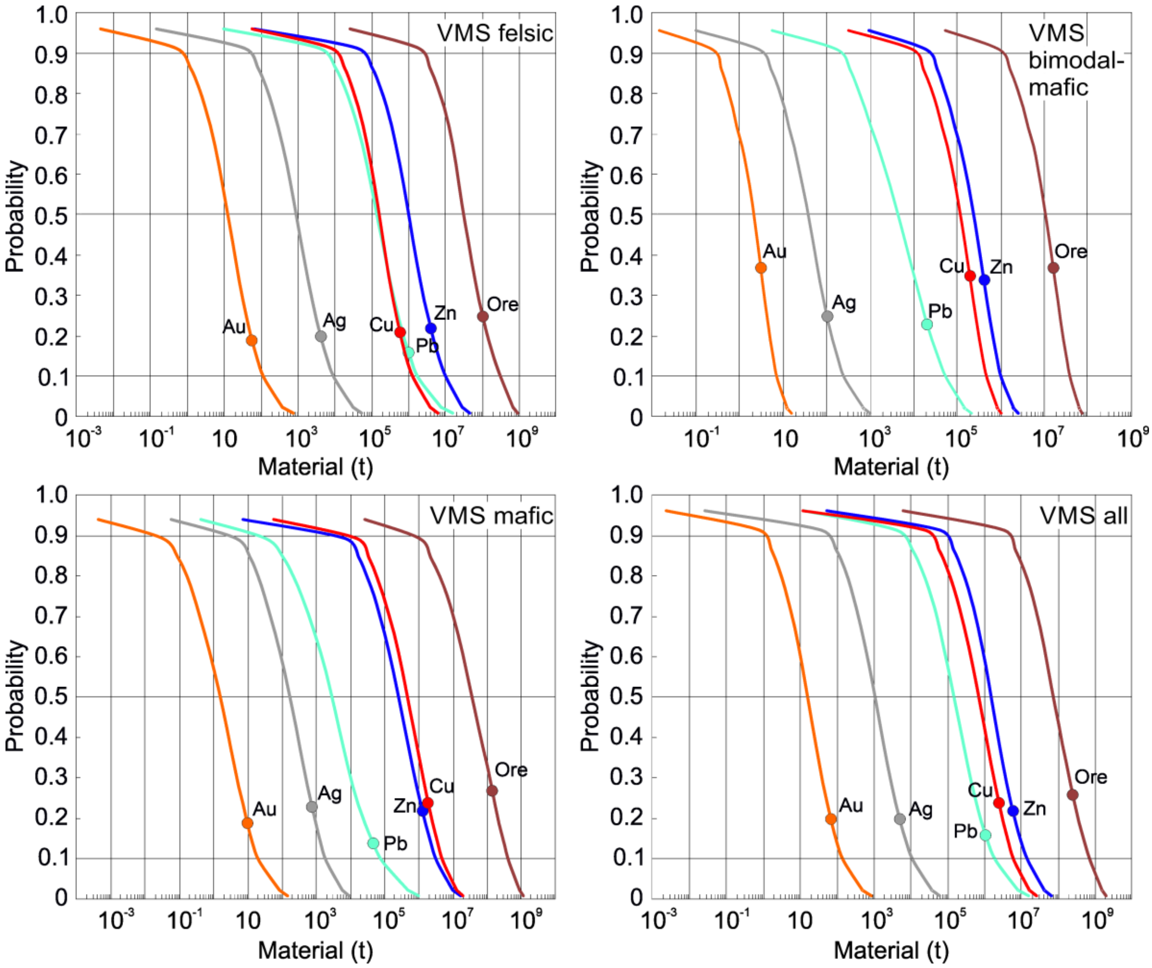

Figure 3. An example of Monte Carlo simulation results. Probability distributions of the estimated amount of metals and ore in undiscovered VMS deposits in Finland (Rasilainen et al. 2014).

3.4.2 Economic analysis

The Monte Carlo simulation produces in-situ estimates of commodities and ore in the bedrock. It does not consider the economic feasibility of the undiscovered deposits. Hence, the total estimated undiscovered resources contain parts that reside in deposits that are, at least presently, uneconomic to mine. Economic analysis can be performed to estimate the proportion of undiscovered resources residing in a deposit that might be viable to mine. Resource Assessment Economic Filter (RAEF) software (Shapiro & Robinson 2019a) uses simple engineering mine cost models to analyse the economic viability of the undiscovered deposits produced by the Monte Carlo simulation.

Probability distributions of metal tonnages in the undiscovered deposits estimated by Monte Carlo simulation were the end results of all the GTK assessments. Economic analysis could not be performed in 2008–2019 because the economic filtering capability was disabled in Eminers software, and it was not carried out in the last assessment published in 2023 because of the lack of compatible output from Eminers to be read in RAEF economic filter software.

3.5 Reliability and usability of the estimates

To avoid biased estimates, it is important that the parts of the method are consistent with each other (Fig. 4). The grade-tonnage model must be consistent with the descriptive model and with the known deposits in the area. The deposits accepted in the deposit density model have to be consistent with the descriptive model and the grade-tonnage model. The permissive tracts delineated must be consistent with the descriptive model. The number of deposits estimates must be consistent with the size distribution of the deposits according to the grade-tonnage model. This means, for example, that 50 % of the estimated undiscovered deposits must be larger than the median tonnage of the deposits according to the grade-tonnage model, and 10 % of the estimated deposits must be larger than the 90th percentile of the deposits according to the model.

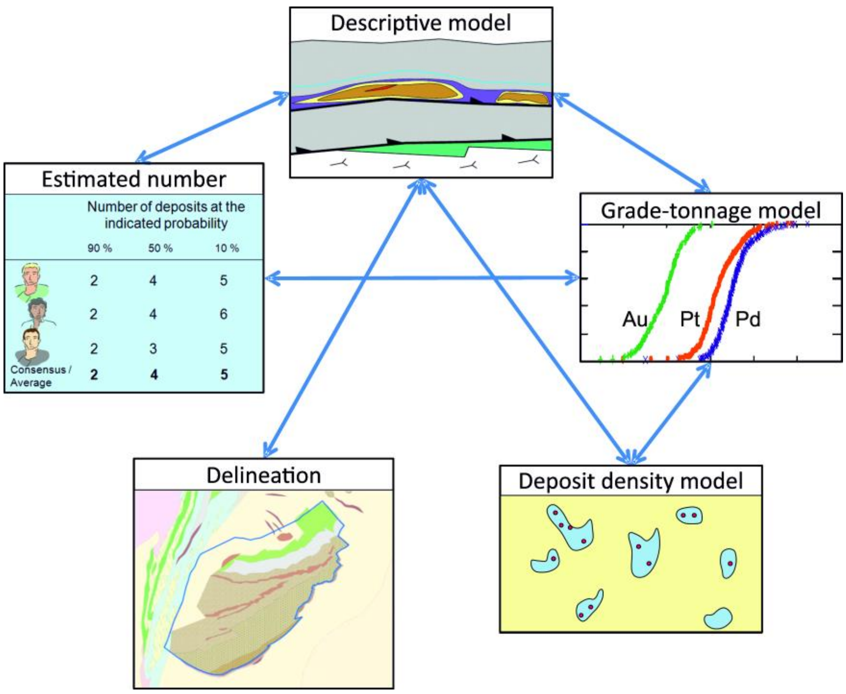

Figure 4. Consistency requirements for the components of the three-part method.

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 uncertainty in the assessment results are associated with the grade-tonnage models used. It is very important that the grade-tonnage model represents, as accurately as possible, totally delineated complete deposits of the correct deposit type. However, even deposits that are considered well known may contain undiscovered resources. This means that some percentage of the deposits of the grade-tonnage model might be incompletely delineated, and the model might underestimate the metal content of the undiscovered deposits.

Furthermore, the method gives the probability of existence, not of discovery. Although the assessment method predicts the existence of some number of undiscovered deposits, it gives no guarantee that any these deposits will ever be discovered. Some of the undiscovered deposits estimated to exist might 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 technologies, or their discovery might require exploration expenditures so large they are unlikely to be discovered any time soon.

Finally, as the grade-tonnage models used in three-part assessments are typically based on datasets that 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 might never be mined for one or more reasons, including low tonnages or grades, deep burial, or occurrence in or near environmentally sensitive areas or areas designated for other land uses than mining.

4 THE ASSESSMENT PROCESS

The working process used in the GTK assessments evolved throughout the lifetime of the project during 2008–2021. This chapter describes the recommended process, which is the outcome of the evolution and includes adjustments and additions based on experience gained during the working period.

The decision to estimate the undiscovered resources of selected commodities in a certain area is the starting point of an assessment process. After the decision has been made, the process can be initiated. The assessment process can be divided into several phases (Fig. 5).

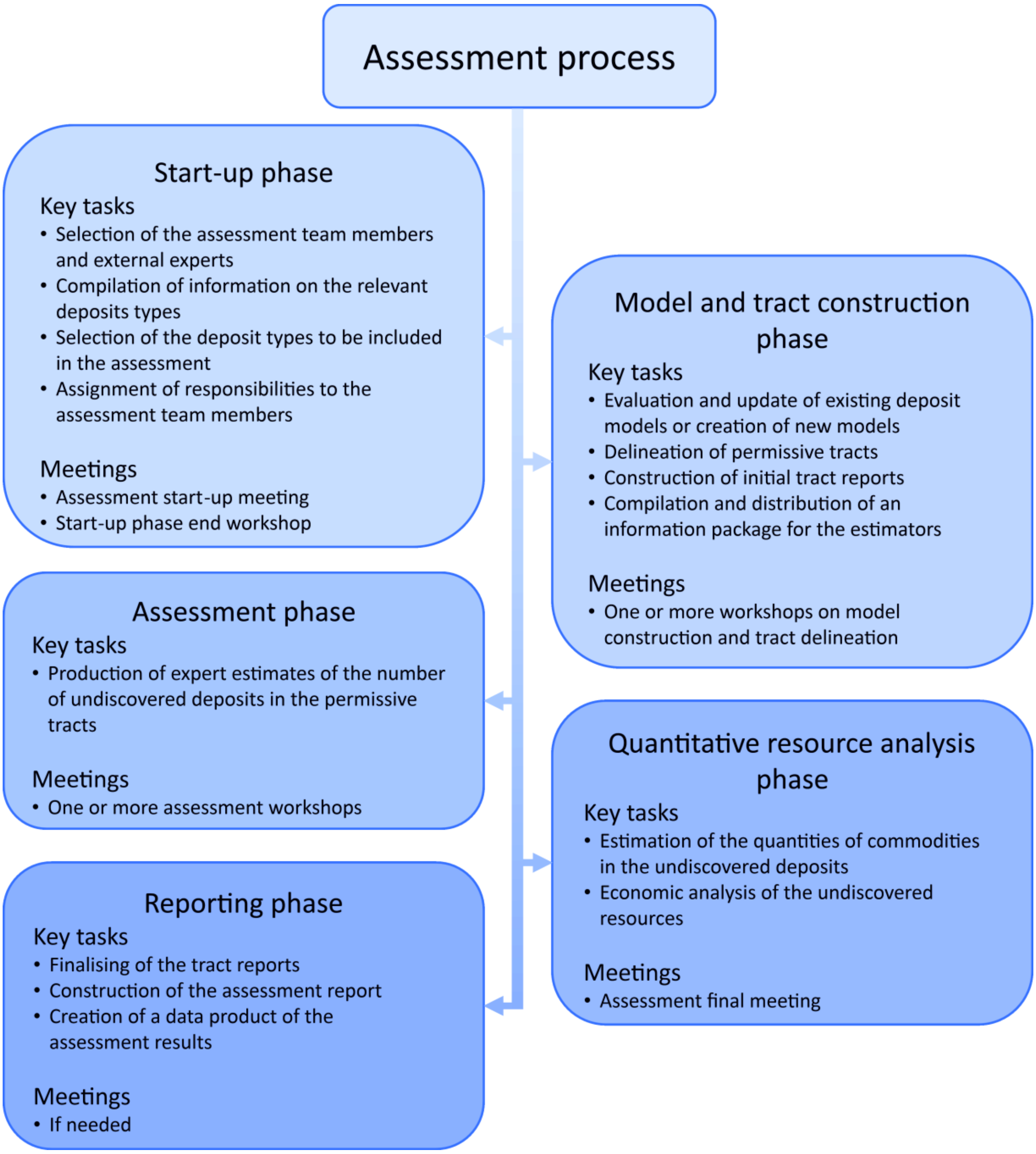

Figure 5. Parts of the assessment process.

The ***start-up phase*** typically includes the forming of the assessment team, arranging of the start-up meeting, and gathering of information on the deposit types relevant for the selected commodities. The phase ends in a workshop where the deposit types to be included in the assessment are selected. In the ***model and tract construction phase***, deposit models are selected or constructed, permissive areas (tracts) for the selected deposit types are delineated and information on the delineated permissive tract areas is compiled. This phase can contain several meetings and workshops, and it ends with the compilation and distribution of an information package to the assessment team members and other experts invited to participate in the assessment workshop. In the ***assessment phase***, the number of undiscovered deposits within the permissive tracts is estimated. The process begins with independent estimates by the experts, and it continues in an assessment workshop or series of workshops, where the estimates are finalised. After the assessment workshop(s), simulations are run in the ***quantitative resource analysis phase*** to calculate the amount of commodities contained in the undiscovered deposits. Economic analysis is performed to find out the economically viable proportion of the total undiscovered resources. The results are evaluated in the final meeting, after which the assessment report is compiled and distributed to the team members for review during the ***reporting phase***. After possible modification due to the review, the report is published, the results are stored in relevant GTK databases, and the assessment process has reached its end.

The assessment process contains several meetings. The nature of the meetings varies from interactive workshops to more conventional meetings, and it is indicated in this document using the terms “meeting” and “workshop”. In addition to the meetings listed in this chapter, gatherings of various combinations of the assessment team members will be necessary at different stages of the project. Although online meetings serve the purpose on most occasions, in some cases it is more effective to have the whole team present in person. The assessment workshop will benefit from all the experts being in the same physical space. Experience gained during the GTK assessments indicates that the discussions concerning the experts’ arguments for their number-of-deposits estimates will be more informative and thorough in a face-to-face situation compared with online communication.

4.1 Start-up phase

After the decision to assess the undiscovered resources of selected commodities in a certain area has been made, the assessment process can be initiated. In the start-up phase, the assessment team is formed, the start-up meeting is arranged and information concerning mineral deposit types relevant for the selected commodities is gathered. The start-up phase ends with a workshop where the deposit types to be included in the assessment are selected and responsibilities for grade-tonnage model construction and permissive tract delineation are assigned to the assessment team members.

The assessment team consists of scientists who will carry out and be responsible for most of the work during the whole process. The selection of the team members is an important step, as the successful performing of an evaluation of undiscovered resources requires knowledge and skills on several fields, including assessment methodology, economic geology, ore geology and metallogeny, bedrock geology, structural geology, geophysics and geochemistry, mathematics, and statistics. Expertise and experience of the specific deposit types to be assessed is crucial, and familiarity with the local geology of areas to be included in the assessment is important. This implies that for the effective and successful completion of an assessment, a large team is required. Experience has shown that there should be at least 10 expert members, and preferably more. A large enough team will prevent the workload of individual experts from becoming too heavy. It should be noted that the assessment team is the core team of experts who will do all the data gathering, model construction, permissive tract delineation and report generation during the assessment. Other experts can be used in the assessment workshop to estimate the number of undiscovered deposits within the permissive tracts. These external experts do not belong to the core assessment team, but they can bring important additional information in the number of deposits estimation process. In the case of GTK, such external experts would typically be scientists from other organisations.

At least some of the experts selected to the assessment team might not be familiar with the assessment method and process. Hence, it is important to arrange a start-up meeting, where the method itself and the workflow of the process are introduced and explained in such detail that the assessment team members and external experts can perform their tasks. It is very important that the external experts who will not participate in the preparation of deposit models or the delineation of permissive tracts are also invited and participate to the start-up meeting. Another important topic to cover in the start-up meeting is the assigning to the team members of responsibilities for information and data gathering concerning the deposit types and geological environments relevant to the assessment at hand.

During the data-gathering period that begins after the start-up meeting, the assessment team members compile information on all relevant deposit types that contain the commodities to be assessed. Information on the location and geological, geochemical, and geophysical characteristics of the deposits and their geological environments within the defined assessment area (e.g., Finland), as well as grade and tonnage data for well-studied deposits is recorded. It is important that the grade and tonnage data recorded is consistent with the existing grade-tonnage models. This means that the spatial rules used in the existing models to define the limits of a deposit must be followed when compiling new grade and tonnage data. Information on indications of mineralisation, like geochemical and geophysical anomalies and ore boulders, should also be gathered.

Not only deposit types known to exist in the assessment area should be included, but also other types of deposits that exist elsewhere and could possibly exist in the assessment area. This is important as several different deposit types may cause similar geophysical, geochemical, and/or other indications in a tract, and confusion may result if such matters are not taken into account when assessing the presence of one type of deposits in an area. Also, a set of deposit types may be products of the same mineral system; if one deposit type is detected, then deposits of the other genetically related type may also be present within a tract.

The data-gathering period ends in a workshop where decisions are made concerning the deposit types that are relevant to be included in the assessment. Responsibilities for the evaluation and possible update of existing descriptive models and grade-tonnage models, or the construction of new models for the selected deposit types are assigned to the assessment team members. Responsibilities for the delineation of permissive tracts and the compilation of initial tract report documents are also assigned to the assessment team members in the workshop.

4.2 Model and tract construction phase

The phase begins with the evaluation of existing deposit models for the selected deposit types. When available, well-established global descriptive and grade-tonnage models should be used. The models should be updated if significant new information is available, or if known local deposits are not consistent with the existing models. New deposit models must be constructed if no applicable models exist.

The work generally begins with the descriptive models, which are required for the delineation of the permissive tracts for the selected deposit types. After the characteristic features of the deposit types and their geological environments have been defined in the descriptive models, this information is used to delineate the permissive tracts.

The delineation of permissive tracts should be performed by the experts most familiar with the geology, mineral deposits, and occurrences of the area. Initial tract boundaries are based on geology and defined so that the probability of deposits of the selected type occurring outside of the tract is negligible. The tract can be extended to areas where the existence of deposits or occurrences of the type being assessed, or geochemical, geophysical, diamond drilling or other data indicate the existence of the permissive geological unit under cover thinner than the assessment depth (commonly one kilometre). Areas of different degree of information quality should be drawn as separate permissive tracts. After the initial drawing of a tract, exploration information is used to exclude barren areas. In an otherwise favourable area, only parts where very thorough exploration extending to the assessment depth has not revealed any occurrences should be excluded from the tract as barren. For each permissive tract, a geological map of the tract area, the criteria used in the delineation of the tract boundaries, information on exploration history, existing mineral deposits, occurrences, and other indications of mineralisation are compiled into an initial tract report document (Appendix 4).

When available, well-established global grade-tonnage models should be used in the assessment. Statistical tests should be applied to ensure the similarity of the local deposits with the global population. Hence, it is critical that the tonnage and grade reporting criteria and the sampling unit criteria (spatial rules for the areal definition of a deposit) for the local deposits are identical to the criteria used in the construction of the global grade-tonnage model. If there is no significant difference between the local deposits and global deposits, the local deposits should be included in the global population and the updated model should be used in the assessment.

If there is a significant difference between the local and global deposit populations, and the local deposits do not form a homogeneous subset of the global population, a new grade-tonnage model should be constructed based on the local deposits. However, the possibility that the local deposits form a biased sample of the true local population should always be considered. A bias might be caused, for example, by a small sample size or different grade and tonnage reporting limits between the local and global deposit datasets.

The construction of a new grade-tonnage model requires that grade and tonnage data are available for a large enough group of well-explored deposits. As a rule of thumb, data for at least 30 deposits should be used to create a grade-tonnage model. The quality of information gathered for the new model must be checked. The resource estimates should cover entire deposits, not only parts of them, and all estimates should be at the same confidence level. As resource data reported according to the present-day industrial standards like JORC (2012), CRIRSCO (2013), NI 43-101 (2011) or PERC (2013) is absent for many older mineral deposits, data that is based on thorough drilling of the apparently entire deposit might have to be used. Any existing model that is updated, and any new model that is constructed, must be included in the assessment report or published separately.

If an existing grade-tonnage model is updated by adding local deposits in the dataset, or if a new grade-tonnage model based on the local deposits is constructed, the corresponding descriptive model must be updated to reflect the possible differences between the local and global deposits.

During the model and tract construction phase, a GIS database containing the relevant spatial information for all permissive tracts is created. An information package containing the GIS data, deposit models and initial permissive tract reports is created and distributed to all assessment team members as well as to all external experts invited to participate to the assessment workshop. Explanations of the assessment method and process, as well as of various guidelines possible to use in the estimation of the number of undiscovered deposits are also included in the information package. The package is distributed to the whole assessment team, and to all external experts.

The model and tract construction phase typically has several meetings and workshops concentrating on the construction and modification of the deposit models and permissive tracts.

4.3 Assessment phase

The assessment phase begins when the information package created in the previous phase is distributed to all the experts invited to the assessment workshop. The phase consists of two parts. In the first part, which takes place before the assessment workshop, the experts are requested to make independent estimates on the number of undiscovered deposits within each of the permissive tracts. The estimates are delivered to that assessment team member who will act as the moderator in the assessment workshop. The moderator summarises the estimates and distributes the anonymous results back to the experts. The second part of the assessment phase consists of the actual assessment workshop or series of workshops, where the estimates of the number of undiscovered deposits within the permissive tracts are discussed and finalised.

Sufficient time should be reserved for the experts to familiarise themselves with the contents of the information package before making their first independent estimates. Depending on the amount of information in the package, at least one month is recommended. The significance of making the first estimates without consulting or discussing with other experts should be stressed. The purpose of the first round of independent evaluations is to capture the full variation of the estimates before narrowing down to a possible consensus value in the assessment workshop.

The experts send their first estimates to the assessment workshop moderator, who summarises the results and distributes them back to the estimators. Anonymity of the experts is maintained in the summary. The preferable way for delivering the estimates to the moderator is to use an online form-based system (for example, Microsoft Forms).

Filling the forms ensures that all experts answer the same questions and deliver all the required information to the moderator. It also makes it easy for the experts to send their estimates to the moderator and for the moderator to summarise the results. An example of an assessment form is given in Appendix 5.

It is possible to bypass the stage of initial pre-workshop independent estimates and have the experts perform all the estimates in the assessment workshop. However, this is not recommended, as it would in many cases give the experts less time to consider their first estimates and might make it more difficult to ensure the independent nature of the estimates.

The actual assessment workshop begins with a summary session concerning the assessment method and process, a review of the work carried out before the workshop, the relevant deposit models, and the delineated permissive tracs. Guidelines to use in the estimation of the number of undiscovered deposits are also reviewed. As this information is included in the information package delivered to all the participants of the assessment meeting, and a part of it was explained already in the start-up meeting, the summary session can be quite short. However, it is useful to review these topics once more to ensure that every participant has the same understanding of them all.

Adjustments to the results of the work carried out in the model and tract construction phase can be done in the assessment workshop, but it is preferable to have the possible adjustments and discussion completed already during the pre-assessment workshop period. Therefore, it is very important to distribute the results of the model and tract construction phase to the whole assessment team and external experts well before the assessment workshop.

After the summary session in the beginning of the assessment workshop, the results of the first round of individual estimates are presented to the participants for discussion. During the discussion, the experts should explain the reasoning for their estimates. The experts can adjust their estimates, in which case the new estimates are recorded, and the old estimates are also saved. The aim of the discussion is to see whether a consensus estimate might be reached. If no consensus is achieved, the median or mean values of the experts' estimates can be used as the final estimate. As all the experts should have the same information, the reason for the inability to reach a consensus should be examined. The reason might be a large amount of uncertainty in the available information, but examination might also reveal differences in the understanding of some of the information used, or inconsistencies in the information, which should then be examined and corrected.

As the last task in the assessment meeting, the estimated numbers of undiscovered deposits for all the permissive tracts should be compared to each other and if required, adjusted to make sure that the estimates are consistent across the tracts. The assessment workshop has been completed when the final adjusted estimates have been recorded for all the tracts. An assessment workshop commonly requires several days to complete, because of the number of permissive tracs to cover and the time the discussions often require. The assessment phase ends when all the assessment workshops have been completed.

4.4 Quantitative resource analysis phase

This phase includes the estimation of the total quantities of metals and ore in the undiscovered deposits, economic analysis of the results and the final meeting where the quantitative assessment results are evaluated.

Monte Carlo simulation is used in the estimation of the amount of undiscovered resources within each permissive tract. In the process, the probability distribution estimated for the number of undiscovered deposits within each permissive tract is combined with the grade and tonnage probability distributions of the grade-tonnage model. The simulation produces the probability distributions of the quantities of contained commodities and ore tonnages in the undiscovered mineral deposits within the permissive tracts. The results are added in the tract report document of each permissive tract (Appendix 4).

To estimate the sum of undiscovered resources for all the permissive tracts, a separate simulation run is required. As it is not statistically correct to add quantile values of several distributions, the number of undiscovered deposits for all the tracts needs to be estimated and used in the simulation. A similar procedure is required for the estimation of undiscovered resources for any combination of tracts. Software to estimate the probability distributions and to perform the Monte Carlo simulations include Eminers (Duval 2012), MapMark4 (Ellefsen 2017, Shapiro 2018, Ross & Lederer 2021), and MapWizard (Rasilainen 2020, Rasilainen & Torppa 2020).

The assessment process described above produces in-situ estimates of metals and ore in the bedrock. It does not consider the economic feasibility of the undiscovered deposits. This means that the total estimated undiscovered resources contain parts that reside in deposits that are uneconomic to mine, at least at present. To reduce this bias, an economic analysis should be carried out after the Monte Carlo simulations. RAEF software (Shapiro & Robinson 2019a) uses the output of MapMark4 or MapWizard as input and applies simple engineering mine cost models to analyse how large part of the simulated undiscovered deposits are likely to be economically viable to excavate. A limited version of RAEF is included into MapWizard. Economic analysis should be carried out for all the simulated undiscovered resources. The results of the economic analysis should be recorded in the tract reports and in the assessment report.

A final meeting is arranged after the quantitative calculations have been completed and the results have been included in the tract reports and the draft assessment report. In the meeting, the results of the whole assessment process are reviewed and evaluated to make sure that they are internally consistent. If no significant bias is observed, the results are considered ready for publishing and the reporting phase can begin. If the results are considered biased, an analysis of the nature and causes of the bias must be carried out, and depending on the results, some parts of the assessment process might have to be repeated.

4.5 Reporting phase

In the reporting phase, the tract reports are finalised, and an assessment report documenting the whole assessment process and its results is created. The descriptive model and grade-tonnage model documents as well as the tract reports are included as appendices to the assessment report. The assessment report is distributed to the assessment team members for review. After possible modification due to the review, the assessment report is delivered to the publishing pipeline of GTK or stored as an internal report if publishing is not considered relevant. The assessment results are stored in relevant GTK databases and made available as a spatial data product via GTK web pages (Hakku service). This completes the reporting phase and the whole assessment process.

The assessment report and the spatial data product are the main outputs of an assessment project. It is imperative that the whole process of producing the estimates and information used is recorded in sufficient detail so that the results can be understood and evaluated. An assessment report should cover at least the following topics:

- Identities of the assessment team members and external experts.
- Start and end dates of the assessment project, dates of the meetings and assessment workshop(s).
- Commodities and deposit types included in the assessment.
- Deposit types excluded from the assessment and the reason for the exclusion.
- Summary of the descriptive models used, and the entire models as appendices.
- Summary of the grade-tonnage models used, and the entire models as appendices.

- Summary of permissive tracts delineated, and the individual tract reports as appendices.
- Summary of the estimates of the number of undiscovered deposits in individual permissive tracts and across all tracts.
- Quantitative estimates of commodity tonnages in the individual tracts and across all tracts.
- Economic analysis of the estimated undiscovered endowment.
- Assessment of uncertainty of the results.

5 SOFTWARE TOOLS

USGS has developed software for the three-part assessments since at least the late 1980s (Drew et al. 1984). Software published by USGS include MARK3 (Root et al. 1992), Eminers (Duval 2012), MapMark4 (Ellefsen 2017), MapMark4GUI (Shapiro 2018) and MapMark4Tiny (Ross & Lederer 2021). These are basically Monte Carlo simulators that estimate a probability distribution for the number of undiscovered deposits, for the grade and tonnage data of well-known deposits, and use these distributions to calculate the probability distribution of the amount of metal and ore in the undiscovered deposits. Early versions of Eminers had an economic feasibility calculation capability, but it was disabled by USGS due to outdated parameter values in 2012.

USGS has published Resource Assessment Economic Filter (RAEF) software (Shapiro & Robinson 2019a) designed to perform an economic analysis of the undiscovered resources estimated by Monte Carlo simulation. RAEF applies engineering mine cost equations to a set of simulated deposits produced by MapMark4 software and estimates the undiscovered resources that might be economic to extract.

USGS has also produced ATA GUI software (Shapiro & Robinson 2019b) for the aggregation of the number-of-deposits estimates across several permissive tracts. The software aggregates undiscovered deposit estimates assuming independence, total dependence, or some degree of correlation among aggregated areas, given a user-specified correlation matrix. ATA GUI outputs three sets of aggregated estimates based on these three assumptions. Monte Carlo simulation can be run using the ATA GUI output to estimate the undiscovered resources in the combined tracts.

GTK has published MapWizard software (Rasilainen 2020, Rasilainen & Torppa 2020), which integrates all the stages of an assessment process into one workflow and has tools to complete each stage. MapWizard is based on MapMark4 code, and it has additional capabilities to produce and store descriptive models, delineate permissive tracts, estimate the number of undiscovered deposits within permissive tracts, combine the results over several permissive tracts, and produce tract and assessment reports. MapWizard can consider the correlation between commodity grades and ore tonnage when performing Monte Carlo simulation, and it implements a simplified version of the USGS RAEF economic analysis code.

All software listed above are freely and publicly available. Links to available software are given in Appendix 6. Beak Consultants Ltd integrated MapWizard code to their commercial advangeo® 2D Prediction software. Further information of the present status of the commercial version is available from Beak (https://www.beak.de).

6 FURTHER DEVELOPMENT DIRECTIONS

The GTK assessments were carried out according to the three-part method and using Eminers in the Monte Carlo simulations. The software has a long history, but recently USGS seems to have stopped developing it and has produced MapMark4 software to perform the Monte Carlo simulations and RAEF software to run economic analysis of MapMark4 results. Because of this, and the reasons listed below, further GTK assessments should use MapWizard software.

- MapWizard is based on MapMark4 code and has additional capabilities and tools to manage a whole assessment project and all parts of the process.
- Logical flow of the assessment process.
- Possibility to select one of two types of grade and tonnage probability density function, and possibility to take into account the covariation of grade and tonnage values when estimating the probability density functions.
- Possibility to choose from three alternative probability mass functions for the number of undiscovered deposits.
- Production of input for economic analysis of the estimated undiscovered resources.
- Possibility to run economic filter software.
- Possibility to estimate the number of undiscovered deposits for a group of permissive tracts based on individual tract estimates and user input.
- Possibility to produce standard tract reports and assessment reports.

6.1 Assessment process development

The three-part assessment method was developed in the 1970s, and the basic principles have not changed notably since then. The three basic parts of the method form a solid and logical framework for an assessment, but the ways the method is applied in an assessment process can vary and evolve.

The recommended way to run the assessment process is described in Chapter 4. Some ideas are listed here for possible future development directions concerning the process and application of the three-part method. Further study and development are required to determine whether implementing any of these ideas could increase the effectiveness and robustness of the assessment process.

6.1.1 Deposit models

Deposit models are an essential component of the three-part method, and they are used in identification and qualitative and quantitative classification of mineral deposits and their geological environments. Descriptive and grade-tonnage models are obligatory for any three-part assessment. Other useful deposit model types include deposit density models and geoenvironmental models.

Deposit density models can be used either directly or as guidelines in the estimation of the number of undiscovered deposits in permissive tracts. The models are based on well-known and thoroughly explored control tracts where all the outcropping deposits of a certain type can be considered known. The general deposit density model is based on 10 deposit types on 109 control tracts and describes linear regression of logarithmic values of deposit density against logarithmic values of tract area and median tonnage of the deposit type (Singer & Kouda 2011). Of these 109 tracts, 33 are of porphyry copper type, 38 of volcanogenic massive sulphide type, and 28 of podiform chromite type. The remaining 10 control tracts represent 7 different deposit types. Hence, the general deposit density model is practically based on only three deposit types.

- An adequate number of control tracts for other deposit types should be added to the general deposit density model. This would increase the representativeness of the model and make its application to any deposit type easier to accept.

Geoenvironmental models can be used in environmental prediction and mitigation, baseline characterization, grass-roots mineral exploration, and assessment of abandoned mine lands and mine-site remediation. As environmental aspects are becoming increasingly important in the minerals industry, geoenvironmental models should evolve to provide relevant information concerning the environmental effects of the undiscovered resources throughout their life cycle.

- Future work should concentrate on adding additional data for different deposit types to make the models more quantitative and capable to predict environmental mitigation expenses and risks associated with mineral extraction.

6.1.2 Permissive tracts

Permissive tracts for a specific deposit type are generally delineated by experts. The tract boundaries are based on geological criteria described in the descriptive model for the deposit type. The criteria for the delineation are clear in principle but they might be difficult to ensure in the real world due to the lack of information, especially at depth. This rule-based delineation process produces areas that are permissive, but it gives no information of the varying levels of favourability for deposits within and between tracts.

- Tract delineation using mineral prospectivity modelling techniques should be investigated (for example, Carranza 2011). These techniques might make it possible to observe the varying favourability within tracts as well as between tracts. The problem is the differing definitions of the terms “permissive” (used in the three-part method) and “prospective” (used in mineral prospectivity modelling).

6.1.3 Number of deposits estimates

The number of undiscovered deposits is usually estimated by experts in a workshop. The estimates are made at three, and occasionally at five, levels of uncertainty. Deposit density models can be used to produce a guideline for the experts, or they can be used to produce the estimate.

- Use of mineral prospectivity modelling techniques in the estimation of the number of undiscovered deposits should be studied.

- New methods for providing guidelines for evaluation should be investigated, for example, Zipf’s law (Lisitsin 2016, Davies et al. 2018), box-counting fractal dimension (Raines 2008) and radial density fractal dimension (Carranza 2011) approaches.

6.1.4 Quantitative resource analysis

Economic filters should be used in resource assessments to estimate which of the simulated undiscovered deposits are clearly economically viable. Presently, the economic filtering is a separate step after the Monte Carlo simulation of undiscovered deposits.

- Implementing the screening of uneconomic deposits into the Monte Carlo simulation process should be investigated.

Possibilities to create a simpler and faster economic screening process should be investigated. For example, a simple 80-20 screener applying the Pareto principle (80 % of the total resource is in 20 % of the largest deposits) might produce a rough but useful estimate of the economically viable undiscovered resource.

6.2 MapWizard development

MapWizard software was developed in an EIT RawMaterials co-funded project “Mineral Resource Assessment Platform (MAP)” during 2018–2020. MapWizard was constructed to manage the whole assessment from the selection or construction of deposits models to the final reporting. The software is modular, with dedicated tools for each part of the assessment process. The development of MapWizard at GTK terminated with the ending of the project and the software code was placed in the public domain and uploaded on GitHub for distribution (Appendix 6).

One of the key points in the MAP project proposal was the implementation of mineral prospectivity modelling tools into the three-part assessment process. This was carried out by developing the Tract delineation tool module as part of MapWizard. However, the Tract delineation tool of the final distribution version (1.4) is cumbersome to use for several reasons:

- GIS software is needed to view intermediate results at several stages.
- The Fuzzy logic process is only partially implemented, as the input evidence rasters must be fuzzy membership rasters instead of rasters of data values.
- The Weights-of-evidence module is implemented to run through the whole process without allowing the user to study the results of the weights generation phase before integrating the evidence layers.
- The Tract delineation tool is very sensitive to differences in input raster coverage, cell alignment, coding of missing data values, and spatial reference system.

The above shortcomings emphasise the fact that MapWizard is not GIS software, and it does not seem sensible to try to develop it into one. The mineral prospectivity modelling tools could be kept in MapWizard future versions, but it might be more effective to concentrate the development resources in other directions. A short summary of the most important development ideas is given below.

6.2.1 General software topics

MapWizard version 1.4 is fully functional, but there are numerous issues that would need to be addressed to make the software more stable and easier to use. These include the following:

- The code should be cleaned and properly documented.
- Better error handling should be implemented. The software should produce clear, informative warning and error messages.
- Default values for all input parameters should be made visible.
- A new genuinely windowed user interface should be implemented. Each window should run under its own independent process, making it possible to run several tools simultaneously.

6.2.2 Descriptive model tool

The Descriptive model tool can be used to create a descriptive model document interactively by text box input. Alternatively, the tool can read in an existing descriptive model in Microsoft Word format. The tool stores the descriptive model and links it to the current assessment project, to be included in the reports generated by the Reporting tool.

- Generating text using text box input is laborious, and there are no formatting capabilities. Text box input should be removed, and the tool should be modified to store the complete descriptive model document created elsewhere and to link it to the active assessment project.

6.2.3 Grade-tonnage model tool

The Grade-tonnage model tool estimates independent probability distributions of the ore tonnage and metal grade values, a joint probability distribution of the ore tonnage and metal grade values, or a probability distribution of metal tonnage values in the data file. If a path to an existing grade-tonnage model or a metal tonnage model created previously by the Grade-tonnage model tool is given, the tool displays the model summary tables and graphs and stores the model for use by the Monte Carlo simulation tool in the active project.

- The tool should be modified to enable reading in metal tonnage data containing several metal columns.
- At present, the tool cannot accept data that include missing commodity or tonnage values, which quite often is the case. The possibility to use some method of data imputation should be implemented to bypass problems with

missing grade or tonnage information in the input files (see Feltrin & Bertelli 2022).

6.2.4 Tract delineation tool

The Tract delineation tool uses mineral prospectivity modelling methods to delineate and classify permissive tracts. The fuzzy logic and weights-of-evidence methods have been implemented. Tract boundaries defined outside of MapWizard can also be imported in the tool. The tool stores the created or imported tract in the assessment project file structure and connects the estimated number of deposits and amount of resources with the tract.

- The mineral prospectivity modelling methods are not completely implemented. The tract delineation tool is complex to use and sensitive to differences in input data properties. Both commercial and freely available GIS software exists that is more versatile and better equipped to handle mineral prospectivity modelling tasks. Hence, further development of GIS capabilities in MapWizard would not be sensible. In later versions of the software, it might be better to remove the GIS capabilities and modify the tract delineation tool to just create a location in the project file system for documenting and storing information and results related to each permissive tract. These include the criteria and techniques used in the delineation of the tract, as well as the estimated number of undiscovered deposits and simulated quantities of commodities within the tract.

6.2.5 Undiscovered deposits tool

The Undiscovered deposits tool estimates a probability mass function for the number of undiscovered deposits that might exist within a permissive tract. The tool uses estimates of the number of deposits at several levels of probability as input, and it can produce three types of probability mass functions: negative binomial, non-parametric and custom.

- The selection of probability mass functions that the tool can generate should be increased. For example, the Poisson distribution should be added.

6.2.6 Economic filter tool

The Economic filter tool estimates the proportion of the total estimated undiscovered resource that can be economically viable for mining. The tool applies simple engineering cost models to estimate the economic resource, and it is a slightly simplified version of USGS RAEF software. A separate Screener module is implemented to provide insight into the distribution of the metal content in the simulated undiscovered deposits. The module enables calculation of the resource contained in the selected fraction of the largest deposits, or in the selected fraction of the total resource contained by the undiscovered deposits.

- The simplified version of RAEF software implemented in MapWizard is complex and slow to run. There is no guarantee that updates and fixes made in RAEF by USGS will be implemented in MapWizard. Hence, it might be better to remove the RAEF module from the Economic filter tool in future versions of MapWizard.

- The Screener module should be enhanced to enable the use of the Pareto principle in a simple 80-20 screener (20 % of the largest deposits by metal content contain 80 % of the total resource).

- In addition to producing and storing estimates of the economically viable portion of the undiscovered resources, the Economic filter tool should be able to read in such estimates to be used by the reporting tool.

6.2.7 Aggregate tract results tool

The aggregate results tool combines estimates of the number of undiscovered deposits for a group of permissive tracts. It produces an aggregated estimate, which can be used as input in the Undiscovered deposits tool to estimate the probability mass function for the number of deposits in all the tracts in the group.

- At present, the tool produces an aggregated estimate at 90 %, 50 % and 10 % probability levels, which can be input to the Undiscovered deposits tool to receive the probability mass function of the number of undiscovered deposits. The Aggregate tract results tool should be modified to produce the probability mass function of the aggregated estimate, in addition to the 90 %, 50 % and 10 % estimates.

6.2.8 Reporting tool

The Reporting tool uses ASCII files output by several other MapWizard tools, as well as interactive input and user-defined MS Word files containing additional information. The tool combines all input files into a standard format Tract report or Assessment report and saves the report in a Microsoft Word document format.

- As the tool only combines the input files, the produced report needs manual formatting. As an alternative, the tool should also produce a list of all the input files and store the files in the same directory, to be combined and edited by the user’s editor of choice.

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8 APPENDICES

Appendix 1 Links to GTK assessment reports published 2008–2023

Appendix 2 Descriptive model for orogenic gold

Appendix 3 Grade-tonnage model for carbonatite- and peralkaline intrusion-related REE-P deposits

Appendix 4 Tract report for Kuusamo Co-Au permissive tract

Appendix 5 Assessment forms for estimating the number of undiscovered carbonatite- and peralkaline intrusion-related REE-P deposits in Finland

Appendix 6 Links to publicly available software tools

ELECTRONIC SUPPLEMENTS

ES 1 Deposit density model calculators

ES 2 Eminers grade-tonnage models used in GTK assessments

APPENDIX 1

Links to GTK assessment reports published 2008–2023

Table A1. List of GTK assessment reports published during 2008–2023

Year	Deposit type	Commodities	Reference	Link
2010	Mafic-ultramafic layered intrusion-hosted PGE	Pt, Pd, Au, Cu, Ni	Rasilainen et al. 2010a	https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_180.pdf
2012	Synorogenic intrusion-related Cu-Ni, Komatiite-related Cu-Ni(-PGE)	Ni, Cu, Co Ni, Cu, Co	Rasilainen et al. 2012	https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_194.pdf
2014	VMS deposits, Porphyry Cu deposits, Outokumpu-type Cu-Co-Zn	Cu, Zn, Pb, Au, Ag Cu, Mo, Au, Ag Cu, Zn, Co, Ni	Rasilainen et al. 2014	https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_208.pdf
2015	Orogenic Au	Au	Eilu et al. 2015	https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_216.pdf
2016	Stratiform chromite, Podiform chromite	Cr, Cr	Rasilainen et al. 2016	https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_226.pdf
2018	LCT pegmatite	Li	Rasilainen et al. 2018	https://tupa.gtk.fi/julkaisu/bulletin/bt_406.pdf
2019	Kuusamo-type Au-Co	Au, Co, Cu	Rasilainen et al. 2020	https://tupa.gtk.fi/julkaisu/bulletin/bt_410.pdf
2023	Carbonatite and peralkaline intrusion-related P and REE	P, REE	Rasilainen et al. 2023	https://tupa.gtk.fi/julkaisu/bulletin/bt_415.pdf
	Ortomagmatic Ti-V	Ti, V, Fe	Halkoaho et al. 2023	*In preparation*

APPENDIX 2

Descriptive model for orogenic gold

(Eilu et al. 2016)

APPENDIX 1

DESCRIPTIVE MODEL FOR OROGENIC GOLD DEPOSITS

Eilu, P.[1], Rasilainen, K.[1] and Kontoniemi, O.[2]

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APPROXIMATE SYNONYMS Mesothermal gold, turbidite-hosted gold, greenstone gold, slate belt type, quartz-carbonate vein type, Archaean vein gold, synorogenic gold.

DESCRIPTION Structurally controlled gold deposits formed during orogenies by orogenic fluids (Groves et al. 1998, 2003, Goldfarb et al. 2001, 2005, Weatherley & Henley 2013).

DEPOSIT EXAMPLES

Finland:	
Pampalo	Nurmi et al. (1993)
Suurikuusikko	Patison (2007)
Saattopora	Korvuo (1997)
Jokisivu	Saalmann et al. (2010)

Global:	
Golden Mile	Phillips (1986)
Ballarat	Ramsay et al. (1998)
Hollinger-McIntyre	Smith & Kesler (1985)
Homestake	Caddey et al. (1991)
Mother Lode	Böhlke (1989)

GEOLOGICAL ENVIRONMENT

Host rocks Any rock type within an orogenic belt (i.e., within a greenstone or schist belt). Any metamorphosed supracrustal rock, dyke or intrusion within, or intrusion bounding, such belt. Not present in post- or anorogenic intrusions or unmetamorphosed supracrustal rocks. The favoured host is the locally most reactive and/or most competent lithological unit.

Age In Finland, Neoarchaean (2.70–2.64 Ga) and Palaeoproterozoic (1.91–1.77 Ga). Globally, mineralisation also peaks at ca. 2.1 Ga, Neoproterozoic (700–600 Ma), Silurian to Carboniferous (430–300 Ma) and Cretaceous to early Palaeogene (120–50 Ma). These epochs appear to be related to rapid crustal growth and accretionary stages of supercontinents. Mineralisation typically takes place during the last major stage of an orogeny. This is typically reported as the stage D3 or D4 within an orogen. In greenschist-facies settings, mineralisation typically takes place slightly after the metamorphic peak, but at amphibolite facies at the local regional-metamorphic peak.

Mineralisation environment Orogenic belt (greenstone or schist belt).

Tectonic setting Accretional and, especially, collisional orogenic settings. Subduction under an accretionary wedge and a 'fertile' lower crust (e.g. a subducted oceanic crust) are suggested to significantly enhance the local mineralisation potential.

Associated deposit types Placer deposits.

DEPOSIT DESCRIPTION

Ore minerals Native gold, pyrite, pyrrhotite, arsenopyrite, löllingite (high metamorphic grades), scheelite, rutile, Bi, Sb and Te minerals; also chalcopyrite, cobaltite, gersdorffite in the relatively rare cases where base metals are enriched. In an ore body, the total volume of sulphides is <5 %, commonly in the range 1–2 %; more sulphides only tend to occur in BIF.

Texture and structure The ore bodies typically have a strongly flattened ellipsoidal shape, are plate-like and may have a steep or a gentle dip and plunge of ore shoots. An individual ore body can be 0.5–50 m wide and 100 m to 2 km long, and it can consist of a vein network, an *en echelon* vein swarm or just one single large vein. A deposit may comprise several ore bodies. The depth extent of an ore body may well be much larger than its horizontal extent along strike. An individual vein can be <1 cm to 10 m thick and 20–1000 m long. The vein sets typically record multiple fault fracture, fluid flow and mineral precipitation events. In most cases, gold occurs as native gold, free in gangue and with main sulphides, and as inclusions and in fractures of gangue and sulphide grains. In some cases, such as Suurikuusikko and some ore bodies at Wiluna (Western Australia), most of the gold occurs in the lattice of, or as submicroscopic inclusions in, pyrite or arsenopyrite.

Ore control Hosted by a fault or shear zone. Typically, the host is a second or third degree shear zone branching from a regional-scale fault. Locally, the control for mineralisation can also be a fold hinge, a flexure in a fault, an intersection of a fault and a fold hinge or a lithological contact, or an intersection of two faults. A deposit hosted by a BIF may show an apparent strata-bound character, but a detailed inspection will reveal the diagnostic cross-cutting sulphidation fronts within the mineralised rock.

Weathering products Placer gold and saprolite-hosted gold occurrences.

Geochemical signature As, Au, S, Sb, Te, W ± Ag, B, Bi, Co, Cu, Se. Au/Ag consistently >1, typically 5–10.

Geophysical signature Magnetic and electromagnetic (e.g., VLF-R, IP) surveys can be used to map structures and potentially indicate sulphidised zones. In the case of extensive potassic alteration in mafic–intermediate rocks, a radiometric survey may detect the sericitised or biotitised zones related to mineralisation.

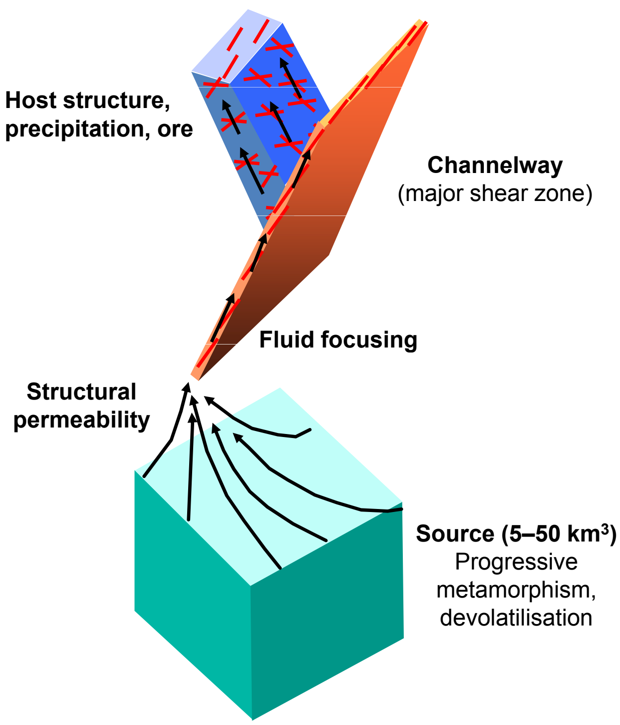

Fig. 1. A schematic view of an orogenic gold system (based on D. Groves, pers. comm. 2003).

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APPENDIX 3

Grade-tonnage model for carbonatite- and peralkaline intrusion-related REE-P deposits

(Rasilainen et al. 2023)

APPENDIX 2

GRADE-TONNAGE MODELS FOR CARBONATITE- AND PERALKALINE INTRUSION-RELATED REE-P DEPOSITS

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INTRODUCTION

This report contains grade-tonnage models for carbonatite-related and peralkaline intrusion-related rare earth element–phosphorus (REE–P) deposits. The descriptive model to be used in three-part assessments of undiscovered resources in these types of deposits was published by Verplanck et al. (2014).

Carbonatites are generally considered as rocks with more than 50% modal primary carbonate minerals and of igneous origin or affinity (Simandl & Paradis 2018). They are commonly associated with intrusive complexes that are rich in alkali metals and show a variety of carbonate substitutions forming calcium-, magnesium- or iron-rich varieties, although they can also be found in peripheral hydrothermal or carbothermal alteration zones adjacent to intrusive phases. The origin of carbonatites is still debated, but several researchers agree on the abundance of alkali elements such as sodium and potassium, needed to form calcite- and dolomite-rich phases from alkalic magmas as residue or cumulates. Carbonatite magmas are typically associated with continental settings, and only 10.5% are non-cratonic (Pirajno 2015). Extensional settings such as reef architectures and hotspot-related island arcs are dominant locations, with extensive linear trends exploited by ascending alkalic and carbonatitic magma. Carbonatites can be suitable hosts of metallic and industrial mineral deposits, including the REE-rich cases. Alkaline-carbonatite complex-related ore deposits represent large resources in terms of REE (e.g., Bayan Obo, Mongolia; Maoniuping, China; Mountain Pass, USA; Mount Weld, Australia). Compared to exclusively peralkaline and alkaline magmas, they are good sources of light rare earth elements (LREE), with a high LREE/REE (total) ratio. This REE fractionation pattern and the high-grade ores render them the primary source of LREE.

Peralkaline suites show deficiencies in the aluminium content, resulting in characteristic felsic and mafic mineralogical assemblages containing abundant potassium and sodium (e.g., sanidine, nepheline, leucite, aegirine, riebeckite). The Otanmäki granites are a Finnish example (Hytönen & Hautala 1985). REE–P deposits are associated with peralkaline rocks, which are largely distinct in three groups: nepheline syenites, alkaline granites and alkaline volcanic rocks (Hoshino et al. 2016). This petrological character is typical of a variety of tectonic environments with common evidence of crustal recycling and rift-related magmatism (Shao et al. 2015, Troll & Schmincke 2002). An important character of peralkaline suites is their relatively low grade (<2 wt%) of rare earth element oxides (REO) compared to carbonatite-related REE deposits, which commonly contain up to 20 wt% REO (Wang et al. 2020). Nevertheless, peralkaline-hosted deposits contain significant amounts of heavy rare earth elements (HREE), which are becoming increasingly important in response to technological advances in electronics and the current transition to clean technology-driven economies. Phosphate is rather connected with agricultural practice, representing an important fertilizer. It is also essential to the production of phosphoric acid used in various industries.

DATA

The data used to construct the grade-tonnage models were gathered from multiple compilations, including Singer (1998), Berger et al. (2009), Weng et al. (2015a,b), Sillanpää (2016), Mihalasky et al. (2017) and Orris et al. (2018). Due to the sparse nature of the available information, historical data were considered acceptable even if in some cases they did not meet modern standards. A spatial rule was used to group deposits that were less than 2000 m from each other to form a single entity.

The initial dataset contained 53 carbonatite-related and 39 peralkaline intrusion-related REE–P deposits representative of global worldwide populations. Four of the carbonatite-related deposits in the dataset are located within the Fennoscandian Shield, three of these in Finland and one in Russia. No peralkaline intrusion-related REE–P deposits with a published resource estimate are known in Finland, but 24 of the deposits in the dataset are within the Fennoscandian Shield. Twenty-two of these are in Russia, one is in Norway and one in Sweden.

Where possible, the grade and tonnage data were verified and updated from company reports and other published information. For a few deposits, no total REE or P grade data could be obtained, and for some others, the available data were considered too uncertain or to represent only a part of a whole deposit. These deposits were excluded during the review process. The process led to the exclusion of four of the 53 carbonatite-related deposits and seven of the 39 peralkaline intrusion-related deposits in the initial dataset. The final datasets of 49 carbonatite-related and 32 peralkaline intrusion-related REE–P deposits are presented in Tables 1 and 2.

The grade-tonnage models used in this assessment require that no grade or tonnage data are missing for the deposits included in the model dataset. However, many deposits for which information was gathered lack either REE or P grade data. To solve this problem, the deposits of both carbonatite- and peralkaline intrusion-related types were grouped into suites (subgroups) based on available grade information: REE+P data, REE data only and P data only. The statistical testing and characterisation were carried out and the grade-tonnage models were constructed for these deposit suites.

The grade-tonnage models constructed consist of probability distributions estimated for ore tonnages and related metal grades. Grades of individual REEs were not used, as they contain significant data gaps, which render them less representative of the data populations. Further to this, REE resources are commonly reported as total REE contents. Total REE data were considered more representative because of a higher degree of completeness and being in line with industry reporting standards.

In the three-part assessment methodology, resource estimates should represent well-explored and totally delineated deposits (Singer & Menzie 2010). Many of the deposits in the dataset are still in production and are likely to be open at depth or laterally. The resource estimates are thus partly informative, and the grade-tonnage models derived using the data may consequently under-estimate the local endowment, since significant resources might remain undiscovered.

Table 1. The final dataset of carbonatite-related REE-P deposits and occurrences used in the development of grade-tonnage models.

Deposit	Country	Cut off (indicative)	Reporting Standard	Age	Tonnage (Mt)	P (%)	REE (ppm)	Reference
Amba Dongar	India	NA	NA	Palaeocene	11.6		9,116	Berger et al. (2009)
Ashram	Canada	0.5% TREO	NI 43-101	Palaeoprote-rozoic	422.74		12,491	Gagnon et al. (2015)
Bayan Obo	China	NA	NA	Mesoprotero-zoic	800		52,000	Drew et al. (1990)
Bear Lodge	USA	1.5% TREO	NI 43-101	Palaeogene	45.2		23,646	Rare Element Resources (2014)
Bou Naga	Maurita-nia	NA	NA	Neoproterozoic	0.1		37,840	Jackson & Christiansen (1993)
Chukt-konskoye	Russia	NA	NA	Permian/ Jurassic	455	7.42	32,508	Berger et al. (2009)
Clay-Howells	Canada	0.2% TREO	NI 43-101	Mesoprotero-zoic	40.422		4,094	Daigle (2011)
Cummins Range	Australia	0.5% TREO	JORC (REE only)	Neoproterozoic	13		9,718	Rarex Limited (2020)
Eureka	Namibia	NA	NA	Cambrian	0.03		54,180	Berger et al. (2009)
Glenover	South Africa	0-0.75% TREYO	NA	Neoproterozoic	28.927	4.15		Van der Walt et al. (2012)
Iron Hill	USA	NA	NA	Neoproterozoic	655.6		3,414	Berger et al. (2009)
Kangankunde	Malawi	3.5% TREO	NA	Cretaceous	2.53		36,500	Lynas Corporation (2007)
Kizilcaören	Turkey	NA	NA	Palaeogene	30		27,004	Yigit (2009)
Kortejärvi	Finland	1.5% P_2O_5	Non-standard	Palaeoprote-rozoic	46.21	1.27	850	Lintinen (2014), Lepistö (2015)
Kovdor	Rusia	NA	Russian standard	Devonian	1936.4	2.96		FODD (2021)
Lavergne-Springer	Canada	0.6% TREO	NI43-101	Proterozoic	49.6		7,500	Daigle (2012)
Lofdal, Area 4	Namibia	0.1% TREO	NI43-101	NA	6.16		2,523	Dodd et al. (2014)
Longonjo (Ozango)	Angola	0.1% NdPrO	JORC	NA	313.7		12,269	Pensana Rare Earths (2020)
Lueshe	Congo	NA	NA	Neoproterozoic	30	3.05		Berger et al. (2009)
Lugiingol	Mongolia	NA	NA	Triassic	0.72		27,520	Berger et al. (2009)
Mabounie	Gabon	NA	NA	Neoproterozoic	360	10.47	21,672	Orris & Chernoff (2002), Jackson & Christiansen (1993)
Maoniuping	China	NA	NA	Palaeogene	107.46		25,400	Liu et al. (2019)
Martison Lake	Canada	6% P_2O_5 or 0.2% Nb_2O_5	NI 43-101	Precambrian	153.4	8.43		Horner et al. (2016)
Montviel	Canada	1% TREO	NI 43-101	Palaeoprote-rozoic	266.6		12,745	Belzile et al. (2015)
Mount Weld P	Australia	10% P_2O_5	JORC	NA	212.7	6.06		Lynas Corporation (2011)
Mount Weld REE	Australia	2.5% TREO	JORC	NA	55.2		46,440	Lynas Corporation (2019)
Mountain Pass	USA	NA	NA	Mesoprotero-zoic	90		43,000	Berger et al. (2009)
Mushgai-Khudag	Mongolia	NA	NA	Cretaceous	367		13,760	Berger et al. (2009)
Ngualla	Tanzania	1% TREO	JORC	Mesoprotero-zoic	214.4		18,490	Peak Resources (2017)
Nkombwa Hill	Zambia	3% P_2O_5	JORC	Neoproterozoic	21.8	3.08	10,062	Vast Resources (2016)

REE: Total rare earth element concentration. TREO: Total rare earth element oxide concentration. TREYO: TREO + Y_2O_3 concentration. NdPrO: Nd_2O_3+Pr_6O_{11} concentration. P and REE concentrations are often calculated from reported P_2O_5 and REO concentrations. NA: Data not available.

Table 1. Cont.

Deposit	Country	Cut off (indicative)	Reporting Standard	Age	Tonnage (Mt)	P (%)	REE (ppm)	Reference
Onduruku-rume	Namibia	NA	NA	Cretaceous	8	3.05	25,800	Berger et al. (2009)
Panda Hill	Tanzania	NA	NA	Cretaceous	480	1.48		Yager (2003), Mchihiyo (1991)
Phalaborwa	South Africa	NA	NA	Palaeoprote-rozoic	652	3.93	1,290	Singer (1998)
Ruri	Kenya	NA	NA	Neogene	3.75		39,200	Berger et al. (2009)
Salitre	Brazil	NA	SEC	Cretaceous	478.4	5.28		SEC (2019)
Sandkopfsdrif	South Africa	NA	NA	Palaeogene	57	1.40	8,600	Singer (1998)
Sarfartoq ST-1 Zone	Green-land	0.6% TREO	NI43-101	NA	12.421		12,176	Druecker & Simpson (2012)
Siilinjärvi	Finland	NA	JORC	Neoarchaean	1,325	1.66		Heino (2019), GTK (2021)
Sokli	Finland	NA	Old	Devonian	12,190.6	1.79		Siirama (2009), Gehör (2010)
Songwe Hill	Malawi	1% TREO	NI43-101	Cretaceous	48.57		11,748	Witley et al. (2020)
St. Honore	Canada	NA	NA	Neoproterozoic	1,058.6		14,921	Grenier & Tremblay (2013)
Storkwitz	Germany	NA	JORC	Cretaceous	4.4		3,870	Deutche Rohstoff (2013)
Sukulu	Uganda	NA	NA	Palaeogene	230.7	5.59		Livingston (1988), Van Kauwenbergh (1991)
Sung Valley	India	NA	NA	Cretaceous	4.56	4.82		Sadiq et al. (2014)
Tapira	Brazil	NA	NA	Cretaceous	1,077	3.54		Gomes et al. (1990)
Wet Mountains	USA		NA	Cambrian	13.96		10,100	Jackson & Christiansen (1993)
Wigu Hill	Tanzania	1% TREO	NI43-101	NA	3.3		22,000	Eggleston & Sides (2011)
Xiluvo	Mozam-bique	1% TREO	JORC	Cretaceous	1.1	1.90	17,443	Southern Crown Resources (2011)
Yangibana Project (juo-nia)	Australia	0.2% NdPrO	JORC	Mesoprotero-zoic	21.673		10,000	Hastings Technology Metals Limited (2019)

REE: Total rare earth element concentration. TREO: Total rare earth element oxide concentration. TREYO: TREO + Y_2O_3 concentration. NdPrO: Nd_2O_3+Pr_6O_{11} concentration. P and REE concentrations are often calculated from reported P_2O_5 and REO concentrations. NA: Data not available.

Table 2. The final dataset of peralkaline intrusion-related REE-P deposits and occurrences used in the development of grade-tonnage models.

Deposit	Country	Cut off (indicative)	Reporting Standard	Age	Tonnage (Mt)	P (%)	REE (ppm)	Reference
Alluaiv	Russia	NA	Russian standard	Devonian	90.06		10,725	FODD (2021)
Apatity Circus	Russia	2% and 4% P_2O_5	Russian standard	Devonian	198.83	6.49	3,175	FODD (2021), Kalashnikov et al. (2016)
Aries, Motzfeldt	Greenland	NA	JORC	Mesoproterozoic	340		2,200	Ram Resources (2012)
Eveslogchorr	Russia	4% P_2O_5	Russian standard	Devonian	517.05		3,775	Kalashnikov et al. (2016)
Høgtuva	Norway	NA	Old	NA	0.35		1,287	EuRare (2021)
Karnasurt	Russia	NA	Russian standard	Devonian	23.46		13,500	FODD (2021)
Kedykvyrpakhk	Russia	NA	Russian standard	Devonian	12.74		13,041	FODD (2021)
Kipawa Lake (Zeus)	Canada	NA	NI43-101	Mesoproterozoic	27.13		3,265	Saucier et al. (2013)
Koashvinskoe	Russia	4% P_2O_5	Russian standard	Devonian	868.32	7.69	3,518	FODD (2021), Kalashnikov et al. (2016)
Kringlerne	Greenland	NA	JORC	Mesoproterozoic	4300		5,600	Stensgaard et al. (2017)
Kuelporr	Russia	4% P_2O_5	Russian standard	Devonian	19.12		2,917	Kalashnikov et al. (2016)
Kuivchorr	Russia	NA	Russian standard	Devonian	550.00		4,976	Kalashnikov et al. (2016)
Kukisvunchorr	Russia	4% P_2O_5	Russian standard	Devonian	502.71	5.34	2,145	FODD (2021), Kalashnikov et al. (2016)
Kutessay II	Kyrgyzstan	NA	Russian code + mined	Upper Permian	42.44		2,800	Stans Energy (2020), Danilov et al. (2011)
Kvanefjeld	Greenland	NA	JORC	Mesoproterozoic	673.00		9,470	Greenland Minerals (2015)
Large Pedestal	Russia	NA	Russian standard	Neoarchaean	10.91		2,831	Kalashnikov et al. (2016)
Lesnoe	Russia	NA	Russian standard	NA	1.51		1,313	FODD (2021)
Nechalacho	Canada	NA	NI 43-101	Palaeoproterozoic	304.63		11,700	Ciuculescu et al. (2013)
Norra Kärr	Sweden	NA	NI 43-101	Neoproterozoic	60.53		5,900	Reed (2011), Weng et al. (2015b)
Nyorkpakhk	Russia	4% P_2O_5	Russian standard	Devonian	100.39	6.88	3,175	FODD (2021), Kalashnikov et al. (2016)
Oleniy Ruchey	Russia	4% P_2O_5	Russian standard	Devonian	403.53	6.83	3,260	FODD (2021), Kalashnikov et al. (2016)
Partomchorr	Russia	4% P_2O_5	Russian standard	Devonian	877.48	3.01	1,716	Bacharach et al. (2011), Kalashnikov et al. (2016)
Rasvumchorr	Russia	4% P_2O_5	Russian standard	Devonian	385.34	5.59	3,003	FODD (2021), Kalashnikov et al. (2016)
Round Top	USA	NA	NI 43-101	Palaeogenic	821.65		681	Hulse et al. (2014)
Sakharjok	Russia	NA	Russian standard	Neoarchaean	35.80		1,070	FODD (2021)
Sørensen	Greenland	NA	JORC	Mesoproterozoic	242		9,450	Greenland Minerals (2015)
Strange Lake (B Zone)	Canada	0.5 % TREO	NI43-101	Mesoproterozoic	492.34		7,278	Gowans et al. (2017)
Vuonemjok	Russia	4% P_2O_5	Russian standard	Devonian	206.47		1,459	Kalashnikov et al. (2016)
Ymperuaiv	Russia	NA	Russian standard	Neoarchaean	10.91		4,719	Kalashnikov et al. (2016)
Yukspor	Russia	4% P_2O_5	Russian standard	Devonian	660.23	6.72	3,346	FODD (2021), Kalashnikov et al. (2016)
Yukspor Lovchorrite	Russia	4% P_2O_5	Russian standard	NA	2.45		6,006	Kalashnikov et al. (2016)
Zone 3	Greenland	NA	JORC	Mesoproterozoic	95		10,700	Greenland Minerals (2015)

REE: Total rare earth element concentration. TREO: Total rare earth element oxide concentration. P and REE concentrations are often calculated from reported P_2O_5 and TREO concentrations. NA: Data not available.

STATISTICS

The statistical workflow adopted had the objective of ensuring that parametric statistics were conducted according to common recommendations requiring input data that are represented by normal or close to normal distributions. The correlation between ore tonnage and commodity grades was assessed to evaluate the level of bias in the final estimates. For instance, a negative correlation between tonnage and grade can lead to an erroneous overestimation of the mineral resources (Ellefsen 2017). Exploratory data analysis was carried out in three steps: (1) scatterplots to identify outliers (Figs. 1 and 2), (2) variable log-transformation to approximate normality, subsequently tested with both the Kolmogorov-Smirnov and Shapiro-Wilk tests (Table 3), and (3) use of Pearson correlation statistics and relative significance (p-value) testing on the log-transformed data to evaluate co-dependence bias (Table 4). As mentioned in the previous chapter, the statistics were conducted on deposit suites based on the available grade information for REE and P.

In step 1, plots of confidence ellipsoids at 95% probability were used to identify potential outliers (Figs. 1 and 2). Since the objective was to obtain models that represent the body of the population and generalize well, outliers identified by the confidence ellipsoids were not excluded unless the reported grade-tonnage data were independently considered too uncertain.

The results of the normality tests in step 2 were used to understand which distributions deviate significantly from the normal curve. The statistical analysis indicated that the distributions of ore tonnage, phosphorous and total REE generally do not significantly differ from lognormality. The only exception to this is suite 1 peralkaline intrusion-related deposits, for which the Shapiro-Wilk test indicates that both P and REE deviate from lognormality at a marginally significant level of 0.013–0.014 (Table 3).

Step 3 revealed weak correlations between logarithmic ore tonnage and commodity grade values (Table 4). However, the probabilities for the correlation coefficients indicate that the correlations are not significant, except for the association of total REEs with P in suite 1 peralkaline intrusion-related deposits. A correlation between P and REE is expected for this deposit style, where apatite is commonly co-precipitated with other REE-enriched minerals (e.g., Kalashnikov et al. 2016).

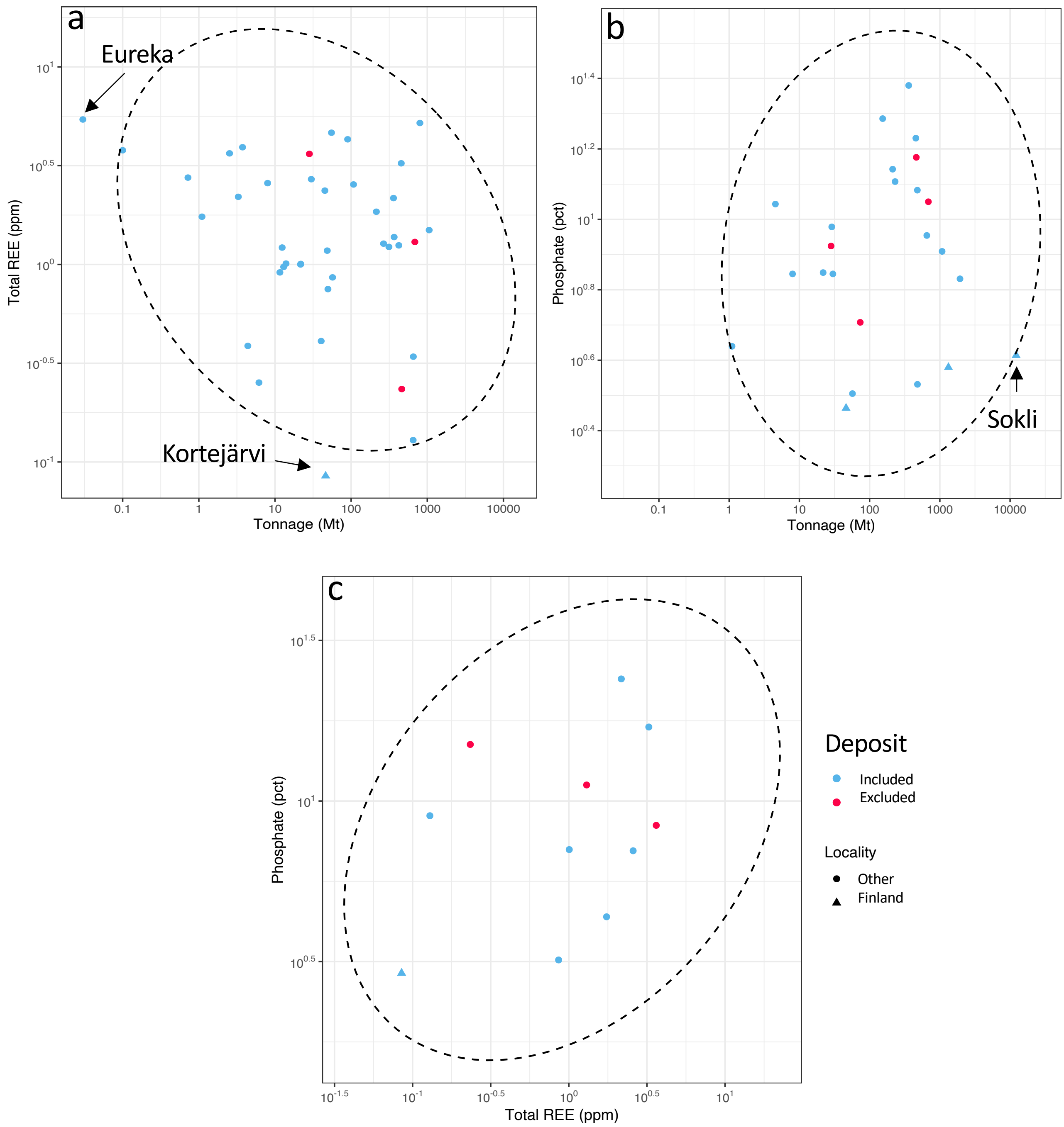


Fig. 1. Relationship between ore tonnage, total REE and P_2O_5 grades for the carbonatite-related REE-P deposits. The plots are based on the initial set of 53 deposits. The 95% confidence ellipsoids are centred on the data means of the x and y variables. One unbiased sample standard deviation of x and y determines their major axes, and the sample covariance between x and y their orientation. The ellipsoid (hatched line) flags outliers. The outliers indicated by the confidence ellipsoid alone were not excluded because of their economic importance and proximity to the global population, and their information quality. Deposits for which the resource data were considered clearly uncertain or incomplete in the data review phase are represented in red and were excluded from the final dataset. The Finnish deposits are shown as triangles.

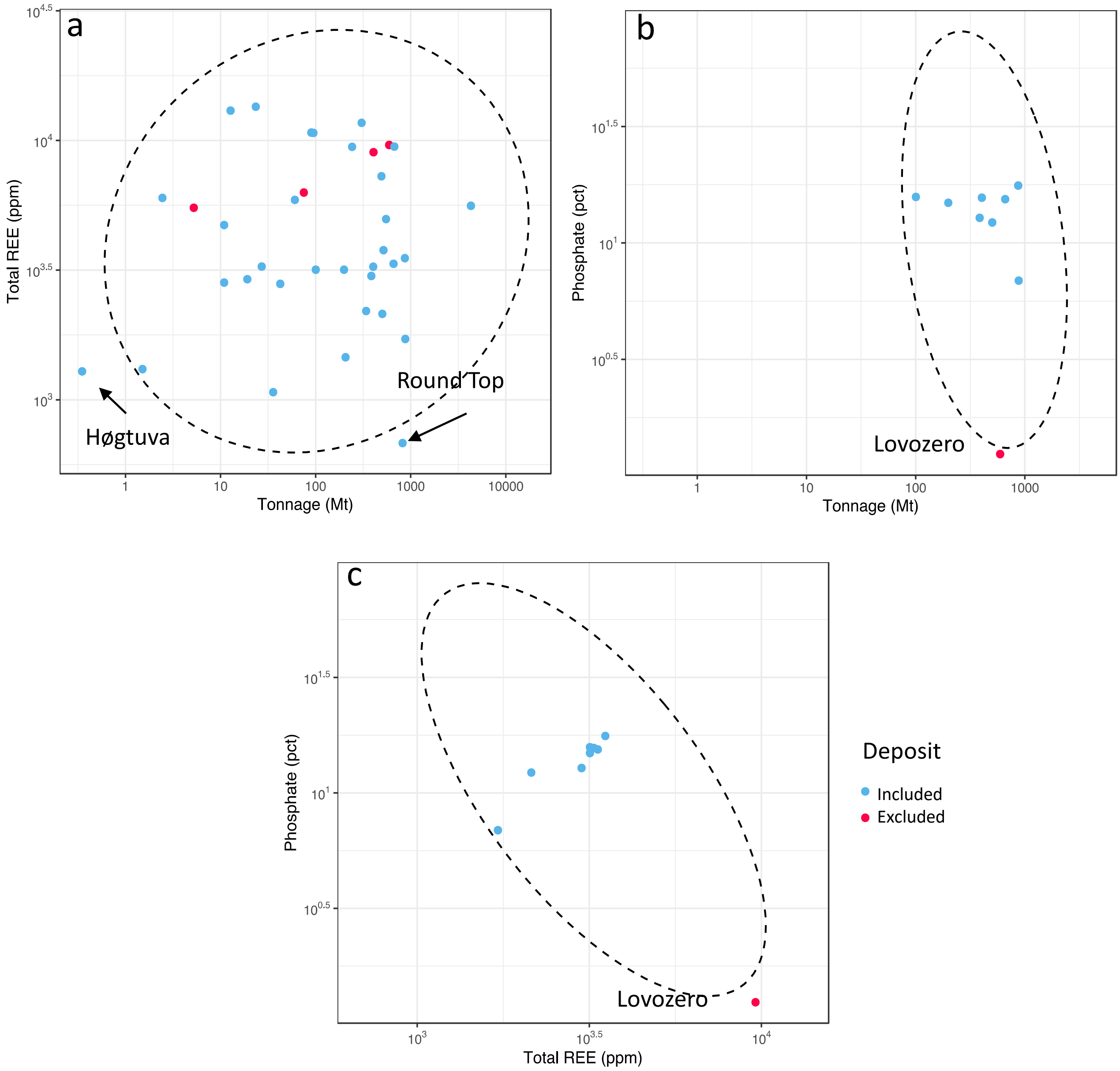


Fig. 2. Relationship between ore tonnage, total REE and P_2O_5 grades for the peralkaline intrusion-related REE-P deposits. The plots are based on the initial set of 39 deposits. The 95% confidence ellipsoids are centred on the data means of the x and y variables. One unbiased sample standard deviation of x and y determines their major axes, and the sample covariance between x and y their orientation. The ellipsoid (hatched line) flags outliers. The outliers indicated by the confidence ellipsoid alone were not excluded because of their economic importance and proximity to the global population, and their information quality. Deposits for which the resource data were considered clearly uncertain or incomplete in the data review phase are represented in red and were excluded from the final dataset. The Finnish deposits are shown as triangles.

Table 3. Tests of lognormality for the carbonatite- and peralkaline intrusion-related deposits in the final dataset.

Deposit Type	Deposit suite	Number of deposits	Variable	Kolmogorov-Smirnov test statistics		Shapiro-Wilk test	
				Statistic	p-value	Statistic	p-value
Carbonatite-related	Suite 1 (P+REE)	8	Tonnage (t)	0.185	0.904	0.937	0.583
		8	P (%)	0.137	0.993	0.941	0.619
		8	REE (%)	0.250	0.614	0.841	0.077
	Suite 2 (P only)	12	Tonnage (t)	0.139	0.949	0.977	0.967
		12	P (%)	0.143	0.939	0.946	0.580
	Suite 3 (REE only)	29	Tonnage (t)	0.172	0.883	0.956	0.740
		29	REE (%)	0.176	0.865	0.924	0.396
Peralkaline intrusion-related	Suite 1 (P+REE)	8	Tonnage (t)	0.218	0.768	0.907	0.331
		8	P (%)	0.258	0.578	0.772	0.013
		8	REE (%)	0.317	0.400	0.804	0.014
	Suite 2 (REE only)	24	Tonnage (t)	0.118	0.870	0.966	0.704
		24	REE (%)	0.117	0.858	0.945	0.210

The test were run separately for the various suites of deposits defined by the available grade data. The test statistics were calculated for logarithmic values. P: phosphorus metal, REE: total rare earth elements as metals.

Table 4. Pearson correlation coefficients and their significance levels for the carbonatite- and peralkaline intrusion-related deposit datasets.

Carbonatite-related deposits				
Suite 1 (REE+P)		Tonnage (t)	REE (%)	P (%)
	Tonnage (t)	1	0.12	0.96
	REE (%)	-0.25	1	0.30
	P (%)	-0.01	0.37	1
Suite 2 (P only)		Tonnage (t)	P (%)	
	Tonnage (t)	1	0.15	
	P (%)	-0.50	1	
Suite 3 (REE only)		Tonnage (t)	REE (%)	
	Tonnage (t)	1	0.22	
	REE (%)	-0.24	1	
Peralkaline intrusion-related deposits				
Suite 1 (REE+P)		Tonnage (t)	REE (%)	P (%)
	Tonnage (t)	1	0.42	0.38
	REE (%)	-0.33	1	0.001
	P (%)	-0.36	0.94	1
Suite 2 (REE only)		Tonnage (t)	REE (%)	
	Tonnage (t)	1		
	REE (%)	0.21 (0.34)	1	

The correlation coefficients are given in the lower diagonal half of the table and the corresponding probabilities (significance levels) in the uper diagonal half. The tests were run separately for the various suites of deposits defined by the available grade data. The test statistics were calculated for logarithmic values. P: phosphorus as element, REE: total rare earth elements as metals.

GRADE-TONNAGE MODELS

The summary statistics for the final carbonatite-related and peralkaline intrusion-related deposit datasets are given in Tables 5 and 6. The grade-tonnage models based on these data were constructed using Eminers software (Duval 2012). Models were constructed separately for carbonatite-related and peralkaline intrusion-related REE-P deposits. Both lognormal and empirical nonparametric models were created. Based on various combinations of existing grade data for REE and P in the dataset, a separate submodel was created for each of the metal suites REE+P, REE only and P only. The statistics of these submodels are summarised in Tables 5 and 6 and Figures 3 and 4.

Table 5. Summary statistics for the grade-tonnage model data for carbonatite-related deposits.

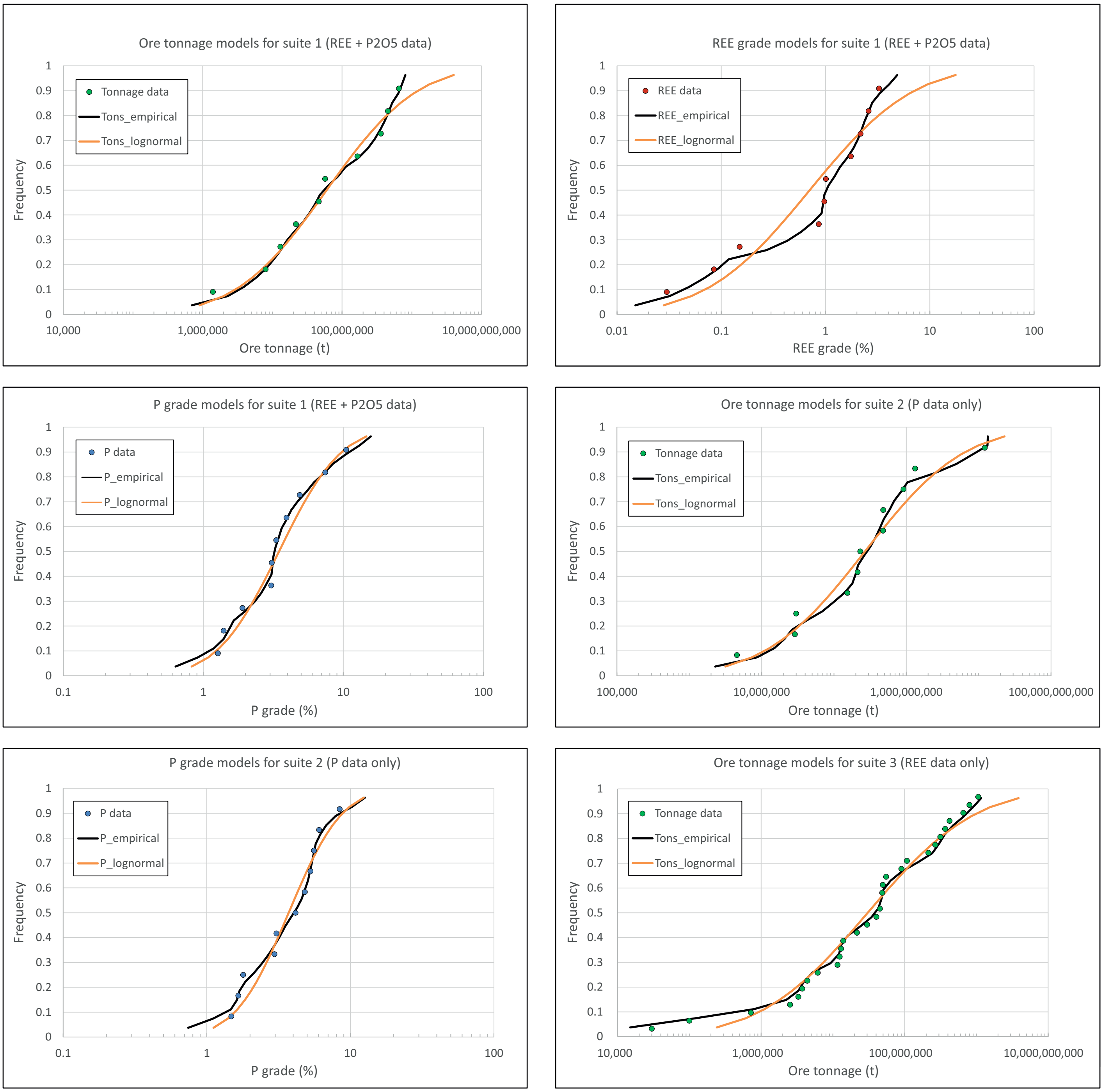
Carbonatite-related suite 1 (REE+P)			
	Tonnage (t)	REE (%)	P (%)
N of deposits	8	8	8
Minimum	1,100,000	0.09	1.27
Maximum	652,000,000	3.25	10.47
Arithmetic mean	200,139,000	1.48	4.07
Standard deviation	252,759,000	1.15	3.25
10th percentile	3,170,000	0.10	1.31
50th percentile	51,605,000	1.38	3.07
90th percentile	592,900,000	3.05	9.56
Carbonatite-related suite 2 (P only)			
	Tonnage (t)	REE (%)	P (%)
N of deposits	12	0	12
Minimum	4,560,000	-	1.48
Maximum	12,190,600,000	-	8.43
Arithmetic mean	1,512,307,000	-	4.07
Standard deviation	3,416,724,000	-	2.08
10th percentile	21,616,900	-	1.61
50th percentile	354,550,000	-	3.85
90th percentile	5,012,660,000	-	6.77
Carbonatite-related suite 3 (REE only)			
	Tonnage (t)	REE (%)	P (%)
N of deposits	29	29	0
Minimum	30,000	0.25	-
Maximum	1,058,600,000	5.42	-
Arithmetic mean	160,646,100	2.08	-
Standard deviation	267,541,000	1.53	-
10th percentile	1,444,000	0.40	-
50th percentile	40,422,000	1.38	-
90th percentile	562,456,000	4.51	-

The statistics were calculated separately for the various suites of deposits defined by the available grade data. P: phosphorus as element, REE: total rare earth elements as metals.

Table 6. Summary statistics for the grade-tonnage model data for peralkaline intrusion-related deposits.

Peralkaline intrusion-related suite 1 (REE+P)			
	Tonnage (t)	**REE (%)**	**P (%)**
N of deposits	8	8	8
Minimum	100,385,000	0.17	3.01
Maximum	877,477,000	0.35	7.69
Arithmetic mean	499,602,100	0.29	6.07
Standard deviation	287,023,800	0.06	1.44
10^{th} percentile	129,918,200	0.18	3.71
50^{th} percentile	453,119,500	0.32	6.61
90^{th} percentile	874,729,900	0.35	7.45
Peralkaline intrusion-related suite 2 (REE only)			
	Tonnage (t)	**REE (%)**	**P (%)**
N of deposits	24	24	0
Minimum	350,000	0.07	-
Maximum	4,300,000,000	1.35	-
Arithmetic mean	369,980,200	0.57	-
Standard deviation	871,793,700	0.41	-
10^{th} percentile	2,353,914	0.13	-
50^{th} percentile	75,295,000	0.48	-
90^{th} percentile	687,865,000	1.18	-

The statistics were calculated separately for the various suites of deposits defined by the available grade data. P: phosphorus metal, REE: total rare earth elements as metals.



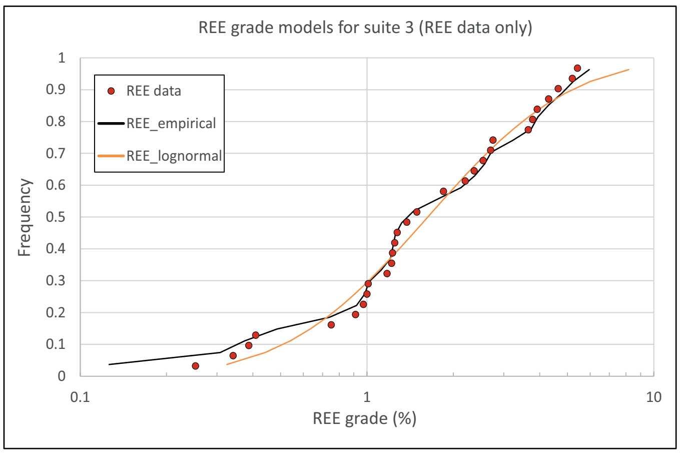


Fig. 3. Cumulative frequency plots of ore tonnage and metal grades for the deposits in the final carbonatite-related REE-P dataset. The three deposit suites were generated based on the available grade data (REE+P, P only, REE only). The data points are shown as coloured circles and estimated empirical and lognormal cumulative distribution functions are shown as solid lines in black and orange, respectively.

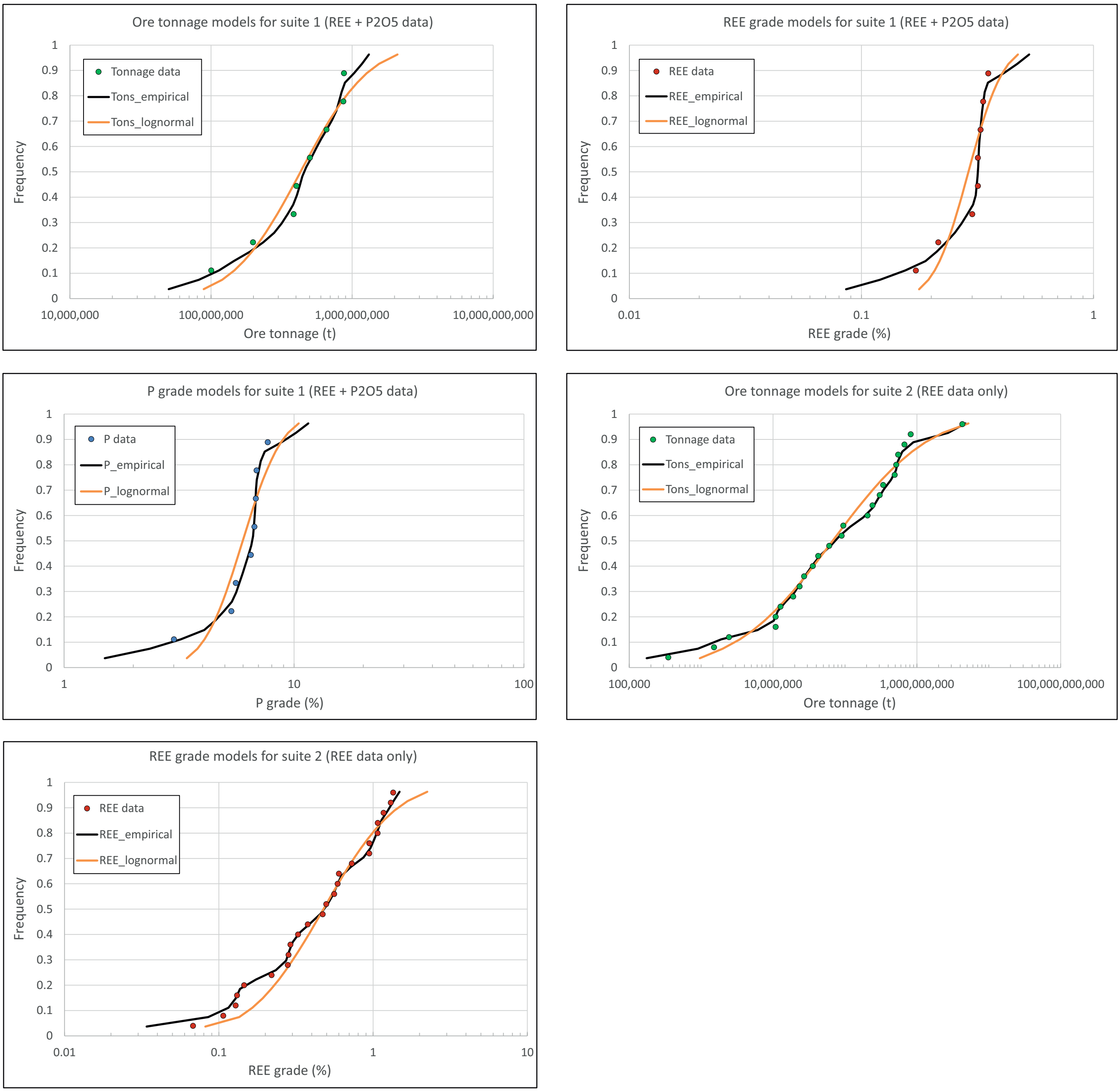


Fig. 4. Cumulative frequency plots of ore tonnage and metal grades for the deposits in the final peralkaline intrusion-related REE-P dataset. The two deposit suites were generated based on the available grade data (REE+P, REE only). The data points are shown as coloured circles and estimated empirical and lognormal cumulative distribution functions are shown as solid lines in black and orange, respectively.

Grade and tonnage data used in the construction of grade-tonnage models should represent total resources, including past production (Singer & Menzie 2010). However, in several cases, this was difficult to fulfil. A large part of the REE-P deposits in the final dataset could obviously be open to depth, along strike, or both, and thus the reported data for them might represent partially discovered deposits. Consequently, the generated grade-tonnage models may under-estimate the local endowment, since significant resources might remain undiscovered. Some inconsistency in reported grades could also derive from the "upgrading effect" caused by supergene enrichments. Furthermore, the data populations in the final dataset are based on global suites of deposits that might consist of multiple local clusters of deposits, which represents an additional level of uncertainty.

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APPENDIX 4

Tract report for Kuusamo Co-Au permissive tract

(Rasilainen et al. 2020)

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	21,698	Co	34,000	Co	28000
			Au	19	Au	27	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 northeast 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)
Lemmonlampi	581539	7337102		0.37	Au (g/t) Co (%) Cu (%)	0.35 0.23 0.52		Korkalo (1987)
Meurastuksenaho	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	Vanhanen (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	Vanhanen (1992)
Isoaho-2	598953	7351749		3 m @ 4 g/t Au	Vanhanen (1992)
Iso-Rehvi	594112	7345212		0.04 Mt @ 4 g/t Au, 0.05% Co, 0.1% Cu	Vanhanen (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	Vanhanen (1991b,c, 2001)
Kuusamon Hanhilampi	598358	7351620		5 m @ 3 g/t Au	Vanhanen (1992a)
Lavasuo	586260	7361388		1 m @ 2 g/t Au	Inkinen (1987)
Murronmaa	589855	7339002		5 grab samples with 1–97 g/t Au	Vanhanen (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	Vanhanen (1992)
Sakarinkaivu-lamminsuo	598933	7354250		2 m @ 2 g/t Au, 9 m 0.13% Co	Vanhanen (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
	Systematic slingram survey 27 km^2		Outokumpu Oyj	1970s–1990s
Drilling	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

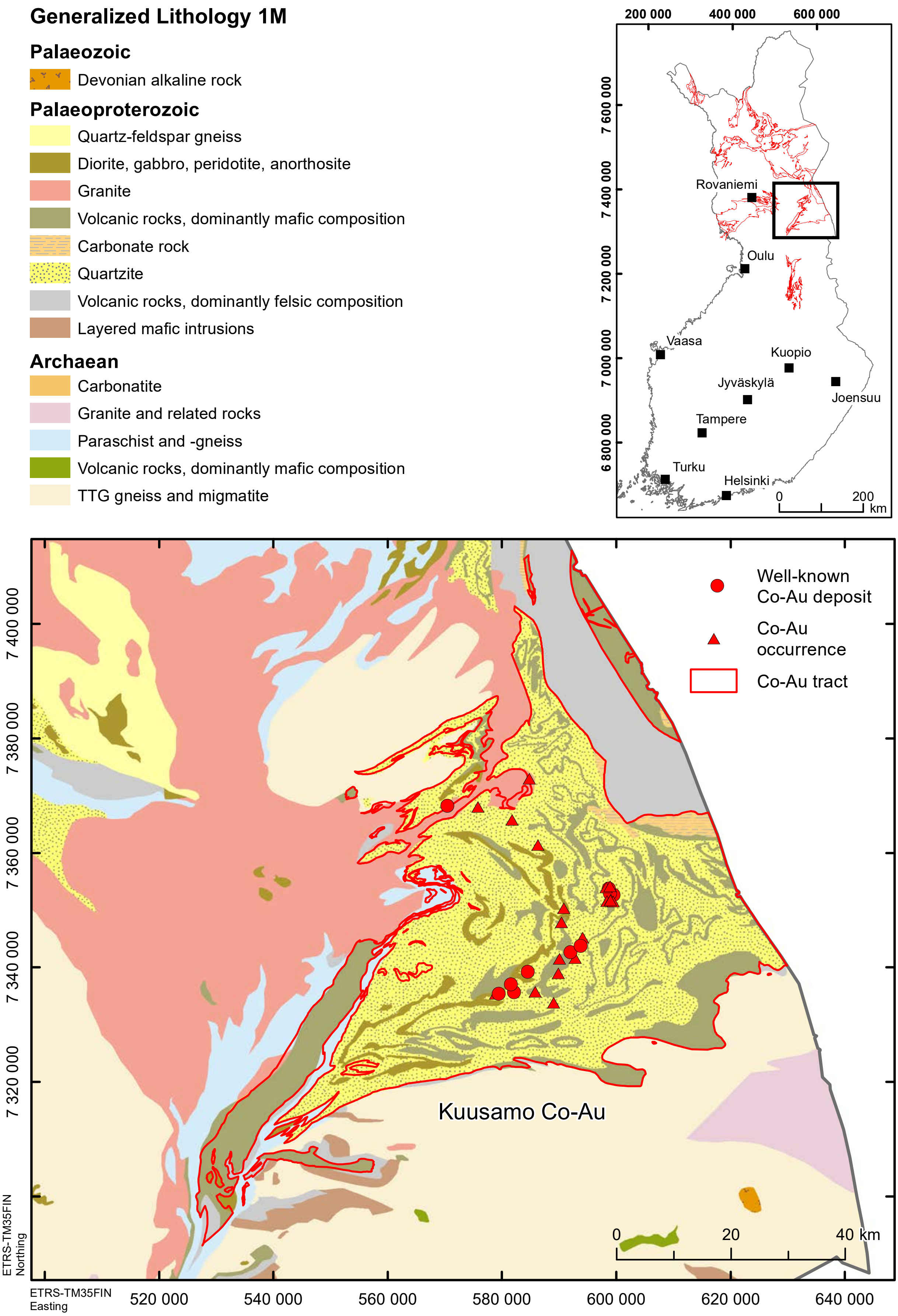

Fig. 1. Location of the Kuusamo Co-Au permissive tract.

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 & Vaasjoki (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 (km²)	Deposit density (N/km²)
N90	N50	N10	N05	N01	N_{und}	s	Cv%	N_{known}	N_{total}		
6	11	29			14	8.7	60	10	24	3,684	0.0065

Estimator	N_{90}	N_{50}	N_{10}	N_{05}	N_{01}
	Estimated number of undiscovered deposits				
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 km^2. 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 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

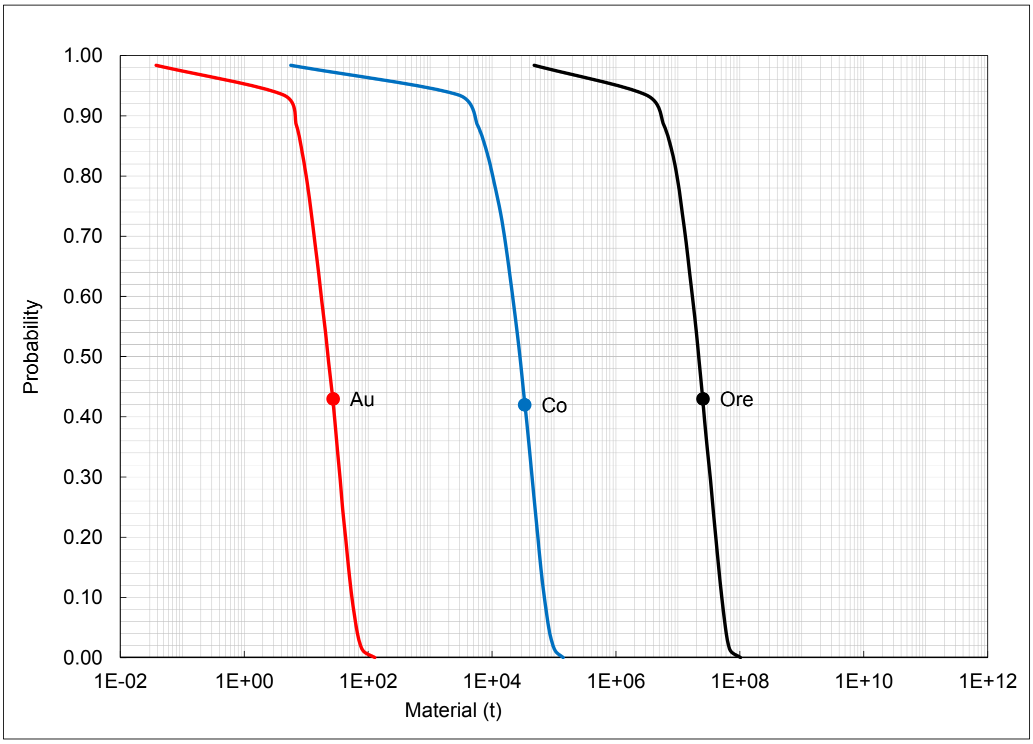

Fig. 2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the Kuusamo Co-Au permissive tract. Labelled dots indicate mean values.

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APPENDIX 5

Assessment forms for estimating the number of undiscovered carbonatite- and peralkaline intrusion-related REE-P deposits in Finland

P-REE deposits in Finland

Assessment of undiscovered P-REE resources in Finland - Number of undiscovered deposits within permissive tracts

* Required

Contact info

1. Enter your email address *

Metadata

2. Assessor name: *

3. Deposit type: *

4. Tract name: *

5. Tract ID:

6. Assessment round *

1	2	3	4	5

Known deposits, significant occurrences and exploration history

Known deposit – A completely delineated in 3 dimensions mineral deposit, for which the identified resources and past production are known.

Deposit – A mineral occurrence of sufficient size and grade that it might, under the most favorable circumstances, be considered to have economic potential. Partially delineated or incompletely known deposits are counted as occurrences or prospects in this assessment.

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

7. Number and names of known deposits

8. Number of partially explored deposits/prospects/occurrences:

9. Exploration history, coverage, intensity:

Estimated number of undiscovered deposits at several probability levels

P90 ≤ P50 ≤ P10 ≤ P05 ≤ P01.
Give the P05 and P01 estimates only if you have given zeros for P90 and P50.

10. P90 *

11. P50 *

12. P10 *

13. P05

14. P01

15. Method of estimation (counting promising prospects, deposit density, anomaly targets, other?)

Supporting data for the estimate of numbers of undiscovered deposits

16. Structures (faults, etc.):

17. Geochemical anomalies:

18. Geophysical anomalies:

19. Radiometric anomalies:

20. Alteration (ASTER, other):

21. Other permissive features:

22. Summary of estimation rationale: *

APPENDIX 6

Links to publicly and freely available software tools

Table A2. Available software tools for the assessment of undiscovered mineral resources.

Software	Publisher	Purpose	Reference	Link to software
MARK3	USGS	Estimate probality distribution for number of undiscovered deposits, ore tonage and commodity grades. Run Monte Carlo simulation of undiscovered resources.	Root et al. (1992)	https://pubs.usgs.gov/of/2000/of00-415/ZIPFile/Install.zip
Eminers	USGS	Estimate probality distribution for number of undiscovered deposits, ore tonage and commodity grades. Run Monte Carlo simulation of undiscovered resources.	Duval (2012)	https://pubs.usgs.gov/of/2004/1344/EMINERS3.0.zip
MapMark4	USGS	Estimate probality distribution for number of undiscovered deposits, ore tonage and commodity grades. Run Monte Carlo simulation of undiscovered resources.	Ellefsen (2017)	http://pubs.usgs.gov/tm/07/c14/MapMark4_1.0.tar.gz
MapMark4GUI	USGS	Estimate probality distribution for number of undiscovered deposits, ore tonage and commodity grades. Run Monte Carlo simulation of undiscovered resources.	Shapiro (2018)	https://pubs.usgs.gov/tm/07/c18/tm7c18_MapMark4Package.zip https://pubs.usgs.gov/tm/07/c18/tm7c18_MapMark4GUIRun.R
MapMark4 Shiny	USGS	Estimate probality distribution for number of undiscovered deposits, ore tonage and commodity grades. Run Monte Carlo simulation of undiscovered resources.	Ross & Lederer (2021)	https://doi.org/10.5066/P96MN574
MapWizard	GTK	Cover the whole assessment process	Rasilainen & Torppa (2020)	https://github.com/gtkfi/MapWizard
RAEF	USGS	Economic analysis of the estimated undiscovered resources.	Shapiro & Robinson (2019a)	https://pubs.usgs.gov/tm/07/c23/tm7c23_package.zip
ATA GUI	USGS	Aggregate estimates of number of undiscovered deposits across tracts.	Shapiro & Robinson (2019b)	https://pubs.usgs.gov/tm/07/c21/tm7c21_ATAGUI_Package.zip
Deposit density calculator	GTK	Estimate the number of undiscovered deposits based on global deposit density models.	Singer (2008)	Electronic supplement
Eminers grade-tonnage models used in GTK assessments	GTK	Gather, transfer and summarise assessor estimates of the number of undiscovered deposits.	This report	Electronic supplement