MAP0001: D5.2: VMS testing report

26 November 2020

KAVA Reference (Number, Acronym, Full Title): 17034, MAP, Mineral Resource Assessment Platform
Name of the author/Responsible partner: NGU,SGU/SGU

Version No:1

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Assessment of VMS deposits in Norway and Sweden, testing the MAP Software

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Acknowledgments

We would like to thank Kalevi Rasilainen for valuable and necessary assistance during the testing of the MAP Wizard. Odleiv Olesen, Janja Knezevic and Aziz Nasuti helped with collection of Norwegian Caledonide data. Michael Stephens, Krister Sundblad and Tor Grenne contributed to the understanding of Caledonian geology and helped with the constructive comments and discussion for the identification and delineation of the permissive tracts. The following are thanked for their expert opinions during the assessment workshops: Tor Grenne, Odleiv Olesen, Kalevi Rasilainen, Henrik Schiellerup, Michael Stephens and Krister Sundblad. This study was conducted through the MAP project. MAP has received funding from the EIT RAW Materials.

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Content

EIT RawMaterials is supported by the EIT, a body of the European Union

1. Introduction

The main purpose of assessing volcanogenic Massive Sulphide (VMS) deposits in certain areas in Norway and Sweden is to test the MAP Wizard software, developed during the MAP (Mineral Resource Assessment Platform) project. The MAP Wizard is a new software combining MPM (Mineral Prospective Mapping) methods and three-part assessment, but also includes an economic filtering tool.

The areas selected for testing of the MAP Wizard software are the Skellefte district in Sweden and parts of the Caledonides on both sides of the Norwegian-Swedish border in the Trøndelag and Västerbotten counties (Figure 1).

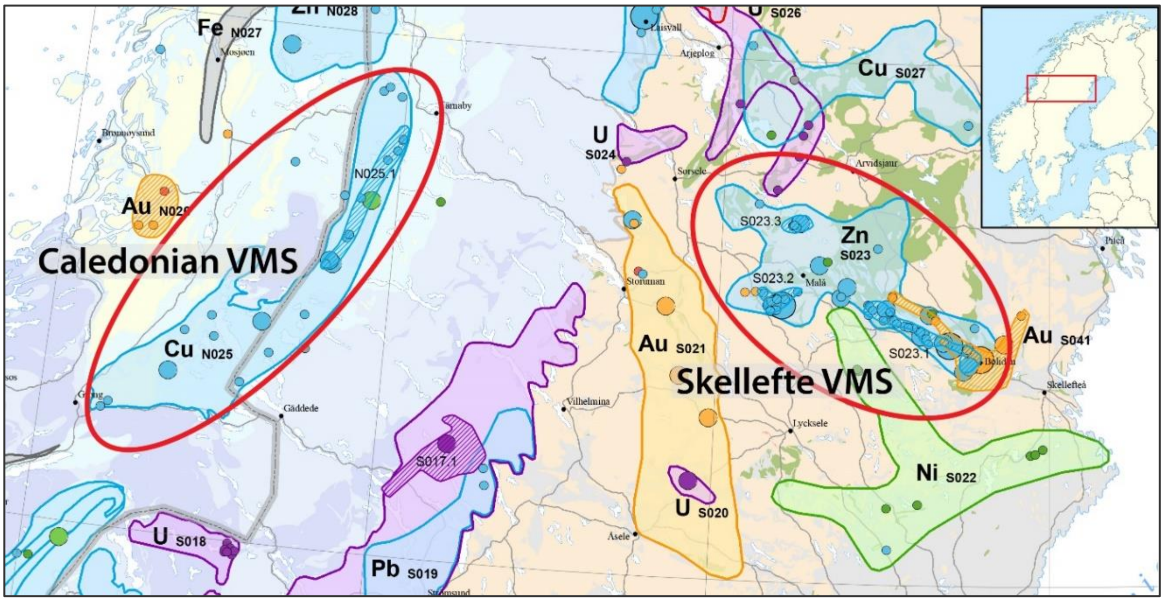

Figure 1: Location of the areas used for testing the MAP software on VMS deposits.

1.1. Terminology

Some terms essential to the proper understanding of this report are briefly described below. The definitions follow the usage by the minerals industry and the resource assessment community (U.S. Bureau of Mines and U.S. Geological Survey 1980, U.S. Geological Survey National Mineral Resource Assessment Team 2000, Committee for Mineral Reserves International Reporting Standards 2013, see Figure 2).

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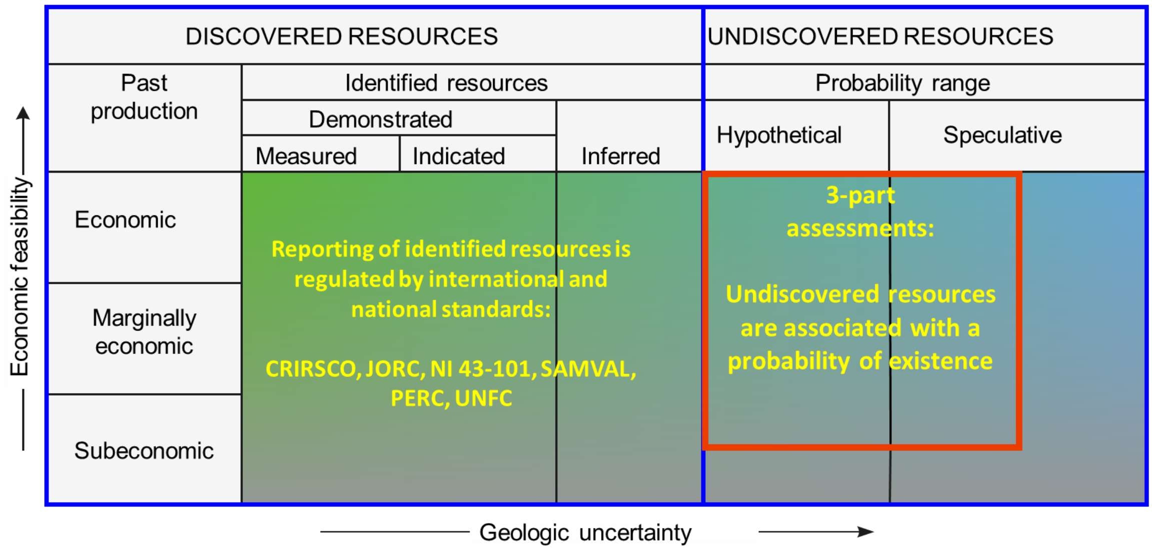

Figure 2: Classification of mineral resources (modified from U.S. Geological Survey National Mineral Resource Assessment Team 2000). Economic feasibility increases upwards and geological uncertainty increases to the right.

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 of ore is known.

Undiscovered mineral deposit
A mineral deposit believed to exist less than 1 km below the surface of the ground, or an incompletely explored mineral occurrence within that depth range that could have sufficient size and grade to be classified as a deposit.

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

Mineral resource
A mineral concentration or occurrence of economic interest in the ground 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. Resources are divided into discovered and undiscovered resources (Figure 2).

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

Well-known resources
Identified resources that occur in completely delineated deposits included in grade-tonnage models.

Discovered resources
The total amount of identified resources and cumulative past production.

Undiscovered resources
Resources in undiscovered mineral deposits whose existence is postulated based on indirect geological evidence.

Hypothetical resources
Undiscovered resources in known types of mineral deposits postulated to exist in favourable geological settings where other well-explored deposits of the same types are known.

Speculative resources
Undiscovered resources that may occur either in known types of deposits in favourable geological settings where mineral discoveries have not been made, or in types of deposits as yet unrecognized for their economic potential.

Mineral potential map
Mapping the likelihood that mineral deposits are present in a study area.

Mineral prospectivity map
Mapping the likelihood that mineral deposits may be found by exploration in a study area.

2. MAP Software

The MAP software is contained in the Map Wizard, which consists of a number of tools to perform an assessment of undiscovered mineral resources in a certain tract (Figure 3). The workflow of the tools in the wizard follows a logical sequence from descriptive model to output of a report of the resource assessment in the given tract (Figure 4).

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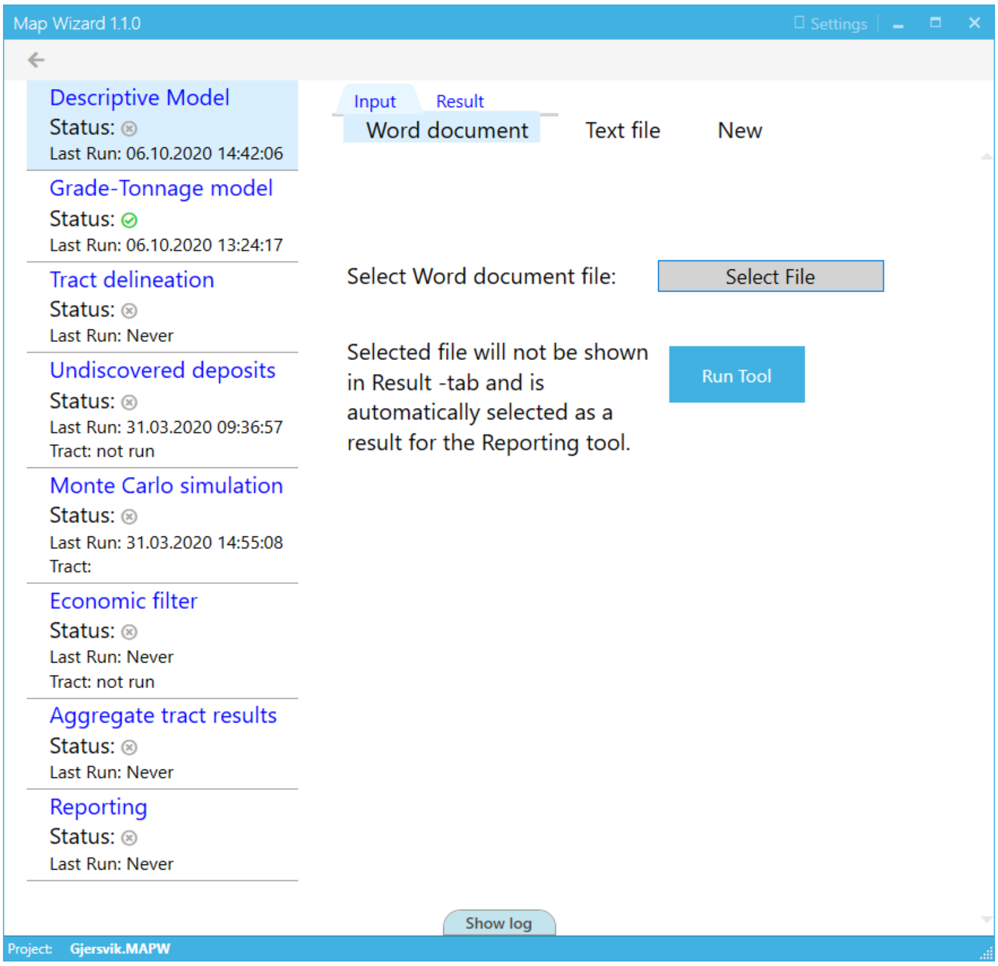

Figure 3: The different tools in the MAP Wizard

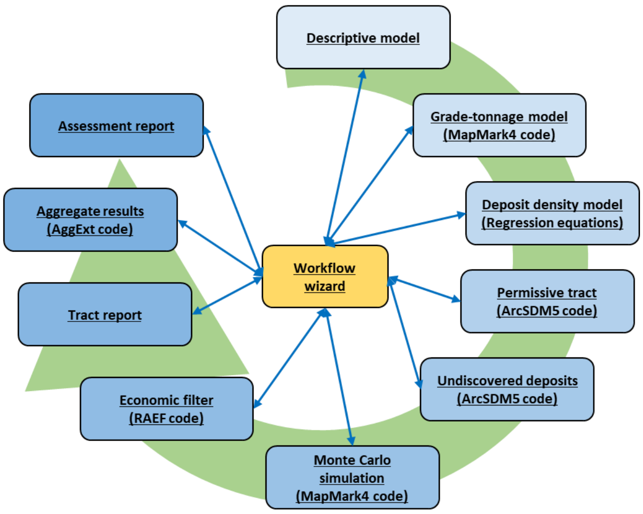

Figure 4: The workflow in the MAP Wizard

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2.1. Descriptions and definitions of the modules in the software

The following descriptions are mainly adopted from Rasilainen et al. (2014).

Descriptive models

A descriptive model consists of systematically arranged information describing the essential characteristics of mineral deposits of the class to be assessed (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 recognized. 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.

Grade-tonnage models

A grade-tonnage model consists of data on average metal grades and the associated total tonnage of well-studied and completely delineated deposits of a certain type (Singer 1993, Singer & Menzie 2010). The total tonnage combines total past production and current resources (including reserves) at the lowest possible cut-off grade. Grade-tonnage models are usually presented as frequency distributions of tonnage and average metal grades. These distributions are used as models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings. They also help in differentiating between a deposit and a mineral occurrence, and in judging whether a deposit or group of deposits belongs to the type represented by the model.

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

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Tract delineation (Permissive tracts)

A permissive tract is an area within which the geology permits the existence of mineral deposits of the type under consideration (Singer 1993, Singer & Menzie 2010). It is important to distinguish between areas favourable for the existence of deposits and permissive tracts: the former are subsets of the latter. The existence of a permissive tract in an area does not indicate any favourability for the occurrence of deposits within the area; neither has it anything to do with the likelihood of discovery of existing undiscovered deposits in the area.

Carranza and Sadeghi (2010) stated that; A number of workers have suggested or demonstrated that Mineral Prospectivity Mapping (MPM) could be included in Mineral Resource Assessment (MRA). Drew and Menzie (1993) introduced conceptual metrics that are useful for estimating indices of favourability of mineral deposit occurrence in geologically-permissive tracts. Raines and Mihalasky (2002) and Raines et al. (2007) have shown that methods for MPM are useful for delineation of geologically-permissive tracts for resource assessment of pluton-related deposits and porphyry copper deposits, respectively. Scott and Dimitrakopoulos (2001) have demonstrated that, in a case study for porphyry copper deposits, MRA complements MPM by providing additional valuable information to support estimation of the number of undiscovered deposits or new exploration targets.

As a guideline to the delineation of permissive tracts prospectivity mapping is suggested. In general, GIS-based MPM can be either data driven or knowledge-driven. Methods of data-driven MPM, which involve quantitative analysis of spatial relationships among anomalies (i.e., indicators of mineralisation) and existing occurrences of mineral deposits of the type sought, are suitable for “brownfields” or well-explored regions, wherein the objective is to define additional targets for exploration. Methods of knowledge-driven MPM, which are based on expert judgment of spatial relationships among anomalies (i.e., indicators of mineralisation) and existing occurrences of mineral deposits of the type sought, are suitable for “greenfields” or under-explored regions, wherein the objective is to define new targets for exploration. Stated differently, both data-driven and knowledge-driven methods are appropriate for data-rich applications, where mineral deposits and their spatial distribution are known, whereas knowledge-driven methods are particularly appropriate for data-poor applications, where mineral deposits are unknown.

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 where 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.

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Undiscovered deposits

The third part of the three-part assessment method is the estimation of the number of undiscovered deposits of the type(s) that may exist in the delineated tracts (Singer 1993, Singer & Menzie 2010). The estimates represent the probability that a certain fixed but unknown number of undiscovered deposits exist in the delineated tracts. The estimates are carried out according to 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 upper 10th quantile of the model. The spatial rule used to define a deposit in the grade-tonnage model must be respected in the estimates. Well-explored and completely delineated deposits, for which published grade and tonnage values exist, are considered as discovered deposits, whereas deposits without publicly available grade and tonnage information, partly delineated deposits, and known occurrences without reliable grade-tonnage estimates are counted as undiscovered.

Several methods can be used either directly or as guidelines to make the estimates. These include the frequency of deposits in well-explored geologically analogous areas (deposit density models), local deposit extrapolations, counting and assigning probabilities to geophysical and/or geochemical anomalies, process constraints, relative frequencies of associated deposit types, and limits set by the total available area or total known metal (Singer 2007). Some of these methods produce a single estimate of the expected number of deposits; others produce a probability distribution of the expected number of deposits. In the latter case, the spread of the estimates for the number of deposits associated with high and low quantiles of the probability distribution (for example, the 90 % and 10 % quantiles) indicates the uncertainty of the estimate. The expected number of deposits, or the estimated number of deposits associated with a given probability level, measures the likelihood of the existence of a deposit type.

The estimates are typically made subjectively by a team of experts knowledgeable about the deposit type and the geology of the region. The process follows the Delphi technique (Chorlton et al. 2007), in which each expert makes an estimate independently and all the estimates are then discussed to possibly reach a final consensus estimate.

Statistical evaluation – 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 tonnages in the undiscovered deposits. Software using Monte Carlo simulation has been developed for this purpose (Root et al. 1992, Duval 2012), and is implemented in the MAP software.

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Economic Filter

The economic filter tool calculates if any proportion of the total estimated undiscovered resource can be considered economically viable for mining. The tool applies simple engineering cost models to estimate the economic resource and it is based on the USGS RAEF (Resource Assessment Economic Filter) code (Shapiro & Robinson 2019).

The Economic filter tool RAEF process allows the same run options as the USGS RAEF software: 1) Batch run mode using a preset parameter file, 2) Interactive run using GUI input of parameters and 3) Run in empirical mode.

A screener process is implemented to provide insight into the distribution of the metal content in the simulated undiscovered deposits. The process enables calculation of the resource contained in a selected fraction of the largest deposits, or in the selected fraction of the total resource contained by the undiscovered deposits.

References

Carranza, E.J.M. and Sadeghi, M. 2010: Predictive mapping of prospectivity and quantitative estimation of undiscovered VMS deposits in Skellefte district (Sweden). Ore Geology Reviews 38, p. 219-241.

Chorlton, L., Laramee, R., Sinclair, D. and Hillary, E. 2007: Data needs and availability. Digital inventory and mineral deposit geology. In: Briskey, J.A. & Schulz, K.J. (eds): Proceedings for a workshop on deposit modeling, mineral resource assessment, and their role in sustainable development, 31st International Geological Congress, Rio de Janeiro, Brazil, 2000. U.S. Geological Survey, Circular 1294, p. 19-28.

Drew, L.J. and Menzie, W.D. 1993: Is there a metric for mineral deposit occurrence probabilities? Nonrenewable Resources, v. 2, no. 2, p. 92-105.

Duval, J.S. 2012: Version 3.0 of EMINERS – Economic Mineral Resource Simulator. U.S. Geological Survey, Open-File Report 2004-1344. [Electronic resource]. Available only at http://pubs.usgs.gov/of/2004/1344. [Referred 2.9.2014].

Raines, G.L., Mihalasky, M.J., 2002. A reconnaissance method for delineation of tracts for regional-scale mineral-resource assessment based on geologic-map data. Natural Resources Research 11, p. 241–248.

Raines, G.L., Connors, K.A. and Chorlton, L.B., 2007. Porphyry copper deposit tract definition—a global analysis comparing geologic map scales. Natural Resources Research 16, p. 191-198.

Rasilainen, K., Eilu, P., Halkoaho, T., Karvinen, A., Kontinen, A., Kousa, J., Lauri, L., Luukas, J., Niiranen, T., Nikander, J., Sipilä, P., Sorjonen-Ward, P., Tiainen, M., Törmänen, T. and Västi, K. 2014: Quantitative assessment of undiscovered resources in volcanogenic massive sulphide deposits, porphyry copper deposits and Outokumpu-type deposits in Finland. Report of Investigation 208, Geological Survey of Finland, 395 p.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Root, D.H., Menzie, W.D. and Scott, W.A. 1992: Computer Monte Carlo simulation in quantitative resource estimation. Natural Resources Research 1, p. 125-138.

Scott, M., Dimitrakopoulos, R., 2001. Quantitative analysis of mineral resources for strategic planning: implications for Australian Geological Surveys. Natural Resources Research 10, p. 159-177.

Shapiro, J.L. and Robinson, G.R. Jr. 2019: Resource Assessment Economic Filter (RAEF)—A graphical user interface supporting implementation of simple engineering mine cost analyses of quantitative mineral resource assessment simulations. U.S. Geological Survey Techniques and Methods, book 7, chap. C23, 18 p. https://doi.org/10.3133/tm7c23.

Singer, D.A. 1993: Development of grade and tonnage models for different deposit types. In Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. and Duke, J.M (eds.): Mineral deposit modelling. Geological Association of Canada, special paper 40, p. 21-30.

Singer, D.A. 2007: Estimating amounts of undiscovered mineral resources. In: Briskey, J.A. & Schulz, K.J. (eds): Proceedings for a workshop on deposit modeling, mineral resource assessment, and their role in sustainable development, 31st International Geological Congress, Rio de Janeiro, Brazil, 2000. U.S. Geological Survey, Circular 1294, p. 79-84.

Singer, D.A. and Berger, V.I. 2007: Mineral resource assessment methodologies. Deposit models and their application in mineral resource assessments. In: Briskey, J.A. & Schulz, K.J. (eds): Proceedings for a workshop on deposit modeling, mineral resource assessment, and their role in sustainable development, 31st International Geological Congress, Rio de Janeiro, Brazil, 2000. U.S. Geological Survey, Circular 1294, p. 71-78.

Singer, D.A. and Menzie W.D. 2010: Quantitative Mineral Resource Assessments. An integrated approach. Oxford University Press, 2010, 219 p.

3. Assessment of VMS deposits – Descriptive model

VMS deposits are stratabound concentrations of sulphide minerals precipitated from hydrothermal fluids in extensional seafloor environments and mostly associated with volcanic lithologies (Koski & Mosier 2012).

Today, VMS deposits are commonly classified based on the associated lithology into mafic-ultramafic, siliciclastic-mafic, bimodal-mafic, bimodal-felsic and siliciclastic-felsic types (Figure 5). For general references, see Barrie & Hannington (1999), Franklin et al. (2005), Galley et al. (2007), Shanks & Thurston (2012).

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Examples
Siliciclastic-felsic: Rio Tinto, Spain (Tornos, 2006)
Bimodal-felsic: Pyhäsalmi, Finland (Mäki & Puustjärvi, 2003), Stekenjokk (this report)
Bimodal-mafic: Horne, Canada (Gibson et al., 2000), Skorovas (this report)
Siliciclastic-mafic: Windy Craggy, Canada (Peter & Scott, 1999), Ankarvattnet (this report)
Mafic-ultramafic: Skouriotissa, Cyprus (Constantinou & Govett 1973), Joma (this report)

Geology (from Shanks & Thurston 2012, Rasilainen et al. 2014)
Rock Types: The composition of volcanic host rocks ranges from mafic to felsic; bimodal mixtures are quite common. The volcanic strata consist of massive and pillow lavas, sheet flows, hyaloclastites, lava breccias, pyroclastic deposits and volcaniclastic sediment. Siliciclastic rocks dominate the stratigraphic assemblage in some settings. Synvolcanic intrusions are common, especially in flow-dominated successions.

Structures and textures: Submarine volcanic structures and textures are common; clastic sediments mixed with dykes and sills, peperites, lava flows, autoclastic breccias, pillows, sheet flows, flow domes and volcaniclastic rocks.

Age Range: Early Archaean (3.55 Ga) to Holocene (presently forming in seafloor settings).

Depositional Environment: Extensional seafloor and subseafloor environment.

Tectonic Setting(s): Mid-oceanic ridges, intra-oceanic and continental margin volcanic arcs, backarc basins, rifted continental margins, pull-apart basins.

Associated Deposit Types: Epithermal Au-Ag, Co-Cu-As in ophiolitic ultramafic rocks.

Mineralogy: Abundant Fe-sulphides (pyrite or pyrrhotite) with variable but generally sub-ordinate amounts of chalcopyrite and sphalerite. Galena occurs as a major component in deposits associated with bimodal-felsic and siliciclastic-felsic lithologies. Accessory minerals include marcasite, magnetite, cobaltite, arsenopyrite, tennantite and tetrahedrite. For example, bornite, stibnite, realgar, stannite and cassiterite usually occur as trace minerals, but are abundant in some deposits. Co- and Ni-bearing arsenides, sulpharsenides and sulphides, although rare in most VMS deposits, can be relatively abundant in deposits associated with serpentinised ultramafic rocks in ophiolitic terranes.

Texture/Structure: Undeformed deposit forms include sheets, layers, lenses, mounds, pipes, and stockworks. Characteristic primary structures include fragmental and layered ores at the deposit scale, and blocky, fragmental and sandy zones are characteristic internal features of well-preserved deposits. Sulphide textures vary from massive (100 % sulphide minerals) through semimassive mixtures of sulphides, gangue minerals and host rock to sulphide disseminated in wall rocks.

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Sulphides also form veins, usually with quartz and other gangue minerals, cutting wall rock and earlier-formed massive sulphides. Many deposits are underlain by discordant sulphide-bearing vein (feeder/stockwork/stringer) systems. Massive sulphides are often laterally gradational to bedded or layered sulphide deposits. Many deposits display a zonation of metals within the massive sulphide body from Fe+Cu at the base to Zn+Fe±Pb±Ba at the top and margins.

Alteration: Pervasive alteration zones characterized by secondary quartz and phyllosilicate minerals reflect hydrothermal circulation through footwall volcanic rocks. The mineralogy of the alteration zones depends on the composition of the ore-forming fluids and the footwall rocks, and on the grade of post-mineralization metamorphism. The most strongly altered rocks are generally in the stringer zone and immediately below the massive sulphides, and the intensity of alteration decreases outward, away from the deposit. Alteration may extend to the hanging-wall rocks if hydrothermal activity continued after burial of the deposit. Semi-conformable alteration zones clearly discordant to regional metamorphic isograds occur in many VMS districts. These zones can be traced over several kilometres of strike length, and they are probably related to premetamorphic horizontal hydrothermal circulation driven by the heat of underlying intrusive bodies.

Ore Control: Controlling features include calderas, craters, grabens, domes, (synvolcanic) faults and fault intersections, seafloor depressions and local basins.

Weathering: Submarine weathering (halmyrolysis) on the seafloor by circulation of oxygenated water is associated with the formation of secondary copper sulphide minerals, but if continued long enough, it will eventually result in the destruction of VMS deposits. Subaerial weathering by descending acidic meteoric water causes mobilisation of metals from primary sulphide minerals and precipitation of copper±gold±silver at depth, forming a supergene enrichment zone overlain by a leached iron oxide-rich gossan. The resulting acid drainage production can cause severe environmental consequences.

Geophysical signature: VMS deposits produce significant electric, electromagnetic, gravimetric and magnetic responses. Potassium enrichment or depletion in wall rocks can produce radiometric anomalies.

Geochemical Signature: High concentrations of one or more of Cu, Zn, Pb. Possibly elevated concentrations of some of Ag, As, Au, Bi, Cd, Co, Ga, Ge, Hg, In, Mo, Ni, Sb, Se, Sn, Tl, W. Depleted Na, especially in footwall rocks. Possibly elevated K. Possibly widespread Fe±Mn±Si±S±Ba±B in exhalates precipitated from VMS-related hydrothermal vents and plumes. Fluid upflow zones often have lower $\delta^{18}O$ values than surrounding areas.

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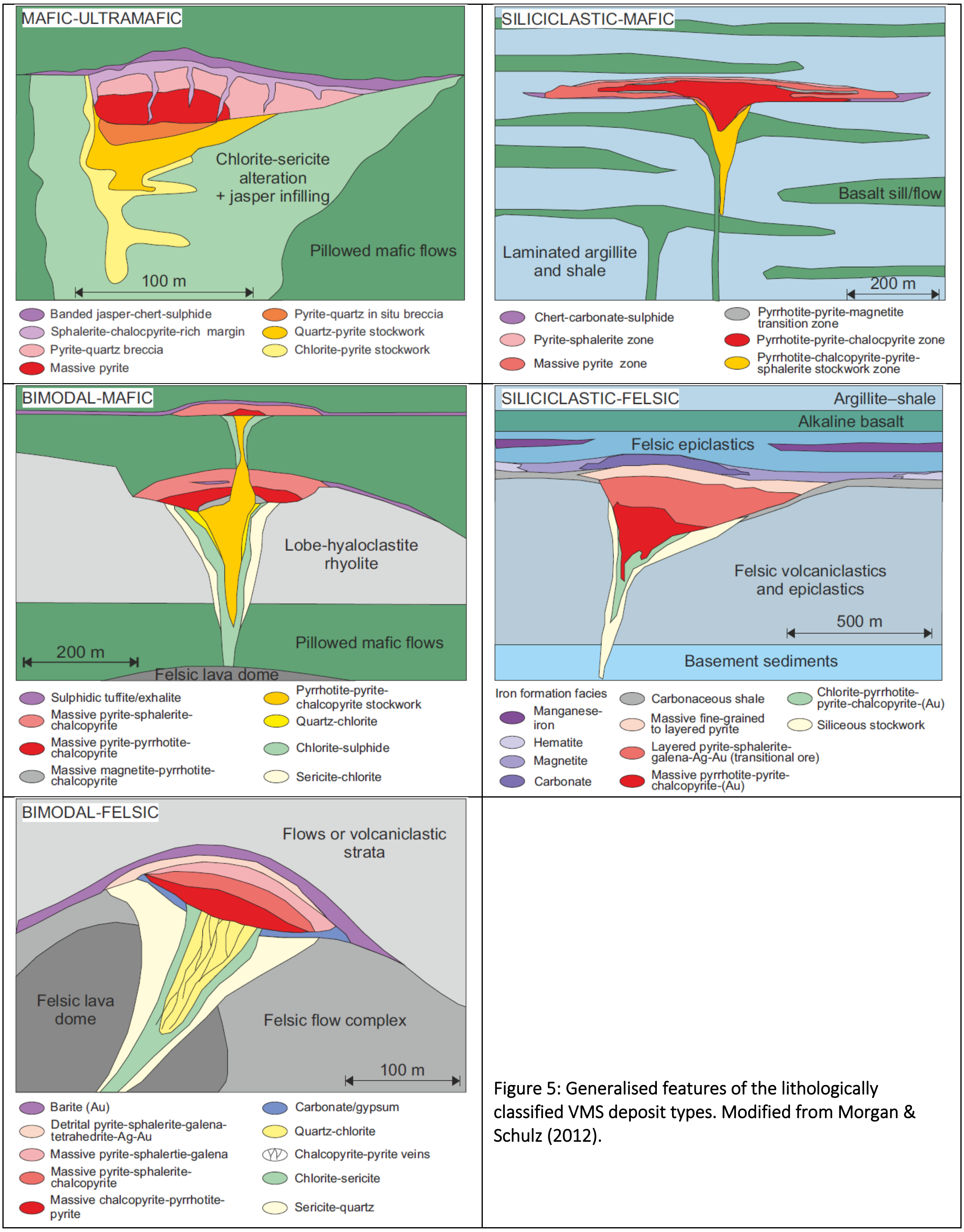

Figure 5: Generalised features of the lithologically classified VMS deposit types. Modified from Morgan & Schulz (2012).

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References

Barrie, C.T. and Hannington, M.D., 1999: Introduction: Classification of VMS deposits based on host rock composition. Reviews in Economic geology no. 8, p. 2-10.

Constantinou, G. and Govett, G.J.S., 1973: Geology, geochemistry, and genesis of Cyprus sulfide deposits. Economic Geology 68, p. 843–858.

Franklin, J.M., Gibson, H.L., Galley, A.G. and Jonasson, I.R., 2005: Volcanogenic massive sulfide deposits. Economic Geology 100th Anniversary volume, p. 523-560.

Galley, A.G., Hannington, M.D. & Jonasson, I.R., 2007: Volcanogenic massive sulphide deposits. In: Goodfellow, W.D. (ed.) Mineral deposits of Canada–A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods. Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p.141–161.

Gibson, H.L., Kerr, D.J. and Cattalani, S., 2000: The Horne mine: geology, history, influence on genetic models, and a comparison to the Kidd Creek mine. Explor. Min. Geol. 9, p. 91-111.

Koski, R.A. and Mosier, D.L., 2012: Deposit type and associated commodities. In Shanks, W.C. Pat, III and Thurston, R., (eds.): Volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070–C, chapter 2, 8 p.

Mäki, T. & Puustjärvi, H., 2003: The Pyhäsalmi massive Zn-Cu-pyrite deposit, middle Finland – a Palaeoproterozoic VMS-class "giant". In: Kelly, J.G., Andrew, C.J., Ashton, J.H., Boland, M.B., Earls, G., Fusciardi, L. and Stanley, G. (eds): Europe's Major Base Metal Deposits. Irish Association of Economic Geology, p. 87–100.

Morgan, L.A. and Schulz, K.J., 2012: Physical volcanology of volcanogenic massive sulfide deposits. In Shanks, W.C. Pat, III and Thurston, R., (eds.): Volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070–C, chapter 5, 36 p.

Peter, J.M. and Scott, S.D., 1999: Windy Craggy, northwestern British Columbia: the world's largest Besshi-type deposit. In Barrie, C.T. and Hannington, M.D., (eds.): Volcanic-associated massive sulfide deposits: processes and examples in modern and ancient settings. Reviews in Economic geology no. 8, p. 261-295.

Rasilainen, K., Eilu, P., Halkoaho, T., Karvinen, A., Kontinen, A., Kousa, J., Lauri, L., Luukas, J., Niiranen, T., Nikander, J., Sipilä, P., Sorjonen-Ward, P., Tiainen, M., Törmänen, T. and Västi, K. 2014: Quantitative assessment of undiscovered resources in volcano¬genic massive sulphide deposits, porphyry copper deposits and Outokumpu-type deposits in Finland. Report of Investigation 208, Geological Survey of Finland, 395 p.

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Shanks, W.C. Pat, III and Thurston, R., eds., 2012: Volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070–C, 345 p.

Tornos, F., 2006: Environment of formation and styles of volcanogenic massive sulfides: The Iberian Pyrite Belt. Ore Geology Reviews 28, p. 259-307.

4. VMS assessment in the Caledonides

4.1. Introduction

Caledonian VMS deposits have been important source for copper, zinc and lead in Norway and Sweden, as well as for sulphur produced from pyrite. Precious metals mainly silver, but also some gold, have been important by-products.

Most of the VMS deposits are situated in the Upper and Uppermost Allochtonous nappe complexes of the Caledonides. These complexes contain volcanic units formed during the opening, spreading and subsequent closure of the Iapetus ocean, a plate-tectonic cycle spanning ca. 300 Ma, starting with rifting in the Neoproterozoic and ending in the Devonian with the collision of Laurentia and Baltica (Grenne et al. 1999).

VMS deposits are present from Finnmark in the north to Rogaland in the south, and from the Norwegian coast in the west across the border into the mountain regions of Sweden in the east (Figure 6).

The Caledonian deposits have been formed in different lithotectonic setting including arcs (immature to mature arcs), back arcs and mid-ocean ridges. The deposits also have different host rocks. Because of this, the deposits fall into different classes of VMS deposits, based on the modern classification scheme by e.g., Shanks & Thurston (2012), including mafic, bimodal-mafic, siliciclastic mafic and bimodal felsic deposits.

The Caledonian deposits have large differences in metal contents, from base-metal poor pyritic deposits to Cu, Cu-Zn and Zn-Pb-Cu dominated deposits and varying tonnage from a few tons to 30-35 Mt (see grade/tonnage section below).

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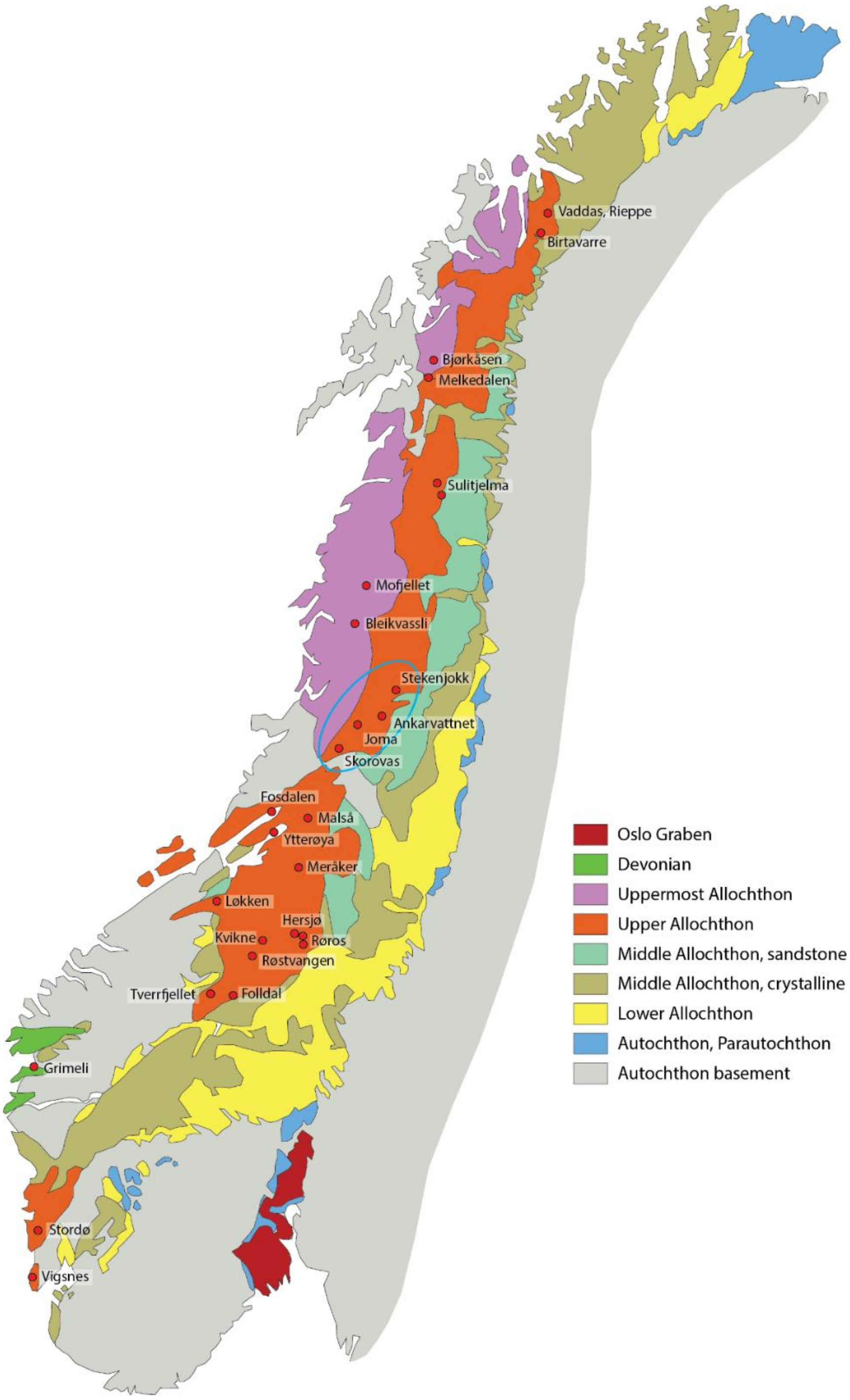

Figure 6: Simplified tectonostratigraphy of the Scandinavian Caledonides with the location of major VMS deposits. The blue ellipse shows the area for this assessment.

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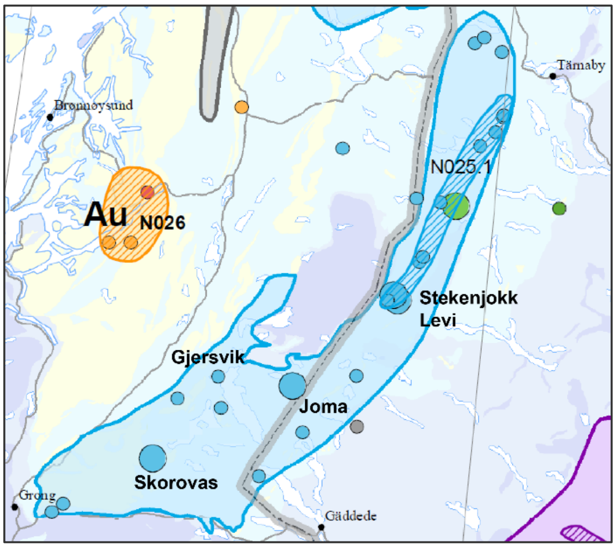
4.2. The Grong-Stekenjokk metallogenic area



The assessment of VMS deposits was decided to be restricted to the Central-Scandinavian part of the Caledonides, specifically the Grong-Stekenjokk metallogenic area defined in the Fenno-scandian Ore Deposit Database (FODD, Figure 7). This region was chosen because it has been subject to substantial mining and prospecting activities, and therefore quite a lot of background data exist regarding geology, geophysics and geochemistry, as well as data on deposits and prospects.

Figure 7: Section of the 1:2 000 000 metallogenic map of the Fennoscandian Shield (Eilu et al., 2009), showing the Grong-Stekenjokk metallogenic area in FODD. Mined deposits are named.

In the FODD the Grong-Stekenjokk area in central Norway and west-central Sweden is defined as one metallogenic area and hosts some of the largest VMS deposits in the Caledonides (Figure 7). Table 1 lists the tonnages, grades, and host rocks for the major VMS deposits in the area. Four mines have been operated in the area, Stekenjokk, Skorovas, Joma and Gjersvik, with a total production of 24.5 Mt in the period 1952–1998 (Sandstad et al., 2012). The other deposits listed in Table 1 have been subjected to test mining.

Figure 8: Location of the tracts for the VMS assessment in the Caledonides.

Because of the differences in lithotectonic setting, the Grong-Stekenjokk metallogenic area has been divided into four subareas, in which the deposits have different host rocks. These areas; Gjersvik, Joma, Stekenjokk and Blåsjön, represent the permissible tracts for this assessment (Figure 8).

Tectonostratigraphically, the area is part of the Køli Nappe Complex in the Upper Allochthon of the Caledonides. The western part comprises the Gjersvik Nappe overlying the Orklump/ Leipikvattnet

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Nappe. The stratigraphically inverted Gjersvik Nappe consists of metavolcanic rocks of the Skorovas Complex (Gjersvik Group) and metasedimentary rocks of the Limingen Group, assumed to represent an immature arc sequence (Sandstad et al. 1997, Grenne et al. 2000). The underlying Orklump Nappe comprises a sequence of predominantly pelagic sediments and basalts in an oceanic setting (Grenne et al. 2000).

The Swedish Stekenjokk-Levi and Ankarvattnet massive sulphide deposits occur in the Stikke nappe. Structurally overlying the Stikke nappe are the Remdalen, Gelvenåkko, Leipikvattnet and Gjersvik nappes. These nappes constitute together the Middle Köli nappes in the Köli nappe complex of the Caledonian orogen. Structurally below the Stikke nappe are the Björkvattnet and Joesjö nappes in the Lower Köli nappes.

Strong similarities in the lithological succession between the different nappes within the Middle Köli nappes indicate that they preserve parts of the same lithostratigraphic units, or units that can be correlated across the Swedish-Norwegian border. This implies that a considerable stratigraphic repetition is present. It also means that parts, or even the entire part, of all the four nappes could potentially be included in permissive tracts for mineral deposits. The stratigraphic succession consists of the Remdalen group, the Stekenjokk quartz keratophyre, the Lasterfjället greenschist and the Blåsjö phyllite lithostratigraphic units (Stephens 1986). The Stekenjokk quartz keratophyre and the Lasterfjället greenschist constitute together the Stekenjokk tract, while the Blåsjö phyllite is a separate tract. Parts of the Remdalen group are included in the Joma tract.

The Joma deposit is hosted entirely by metabasalts in a sequence of predominantly pelagic metasediments in an oceanic setting. The other VMS deposits listed in Table 1 are hosted by metavolcanic rocks of basaltic to rhyodacitic composition, the Skorovass Complex and the Stekenjokk quartz keratophyre, as well as metasediments of the Blåsjö phyllite unit.

The Middle Köli nappes have undergone a polyphase structural evolution (Zachrisson 1969, Sjöstrand 1978, Stephens 1986b, 2020) including development of a D1 fabric, recumbent folding and thrusting during D2, and upright folding during D3. In early studies the stratigraphy was interpreted to be right-way-up, but Stephens (1982) suggested that the sequence is inverted in all nappes.

The tectonic evolution spanning the time period from Cambrian through Ordovician, summarized by Stephens (1980, 1982, 2020), starts with an intra-plate, shallowing-upwards sequence as a forerunner to extensive magmatic activity in an oceanic island-arc setting. Long-lived magmatism of ocean-floor basalt character prevailed during subsequent rifting of the volcanic arc system and formation of a turbidite-infilled back-arc basin. The following Scandian orogenic activity involved polyphase folding, east-vergent thrusting and greenschist facies metamorphism (420°C and 3-5 kbar, Sundblad et al. 1984), that preceded upright, orogen-parallel and orogen-transverse open folding.

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Table 1: Major deposits in the Grong-Stekenjokk metallogenic area.

Deposit	Tonnage (total)	Cu%	Zn%	Pb%	Host rock
Joma	22.45 Mt	1.49	1.45		Basalt
Stekenjokk	11.90 Mt	1.3	3.8	0.6	Rhyodacite, tuffite, graphite phyllite
Skorovas	6.9 Mt	1.14	2.71		Rhyodacite, basalt
Levi	5.1 Mt	1.2	1.8	0.14	Rhyodacite
Skiftesmyr	4.07 Mt	1.0	1.5		Felsic/Mafic tuffs
Gjersvik	1.62 Mt	2.15	0.6		Rhyodacite, basalt
Visletten	0.78 Mt	0.92	3.86		Basalt
Godejord	0.25 Mt	0.6	4.2	0.2	Calcareous and cherty tuffs
Finnbu	0.25 Mt	0.3	3.0		Basaltic tuffs
Ankarvattnet	0.75 Mt	0.45	5.48	0.37	Calcareous metagreywacke
Jormlien	0.61 Mt	0.4	4.75		Calcareous metagreywacke

4.3. Grade-Tonnage model for the Caledonian assessment

Because of restricted number of deposits with grade and tonnage data in the Scandinavian part of the Caledonides, data for deposits within the entire Caledonian-Appalachian orogen are used for the grade and tonnage model for the assessment. This implies that the data set (in the Appendix) includes 81 deposits from Norway, 47 deposits from Sweden, 52 deposits from Canada, 26 deposits from USA, and one deposit each from Ireland and the UK, a total of 208 deposits   A spatial rule has been applied, according to which deposits less than 500 m from each other have been combined.

In this model, we use a fourfold classification of VMS deposits into mafic, bimodal-mafic, siliciclastic-mafic and bimodal-felsic/felsic types. The felsic group contains both siliciclastic-felsic deposits in mature epicontinental arcs and bimodal-felsic deposits in epicontinental and oceanic arc settings.

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Summary statistics for the VMS classes

Siliciclastic-Mafic subclass

	Tonnage (Mt)	Cu %	Zn %	Pb %	Au g/t	Ag g/t
N	38	47	39	17	14	17
Minimum	0.01	0.02	0.03	0.002	0.1	3
Maximum	19.09	9.85	9.40	2.98	3.0	69
Mean	1.98	1.55	2.33	0.58	0.5	22
St.dev	4.31	1.68	2.27	0.92	0.7	21
10%	6.30	3.26	5.48	2.52	1.8	56
50% (median)	0.78	1.20	2.00	0.40	0.4	17
90%	0.06	0.17	0.10	0.004	0.1	3

Mafic subclass

	Tonnage (Mt)	Cu %	Zn %	Pb %	Au g/t	Ag g/t
N	37	37	26	5	7	6
Minimum	0.10	0.50	0.01	0.02	0.1	7
Maximum	30.00	10.00	7.00	0.30	0.9	27
Mean	3.54	1.82	1.57	0.13	0.3	15
St.dev	6.49	1.53	1.49	0.10	0.3	6
10%	12.20	2.84	3.42	n.d.	n.d.	n.d.
50% (median)	1.06	1.50	1.10	0.10	0.2	14
90%	0.19	0.83	0.29	n.d.	n.d.	n.d.

Bimodal-Mafic subclass

	Tonnage (Mt)	Cu %	Zn %	Pb %	Au g/t	Ag g/t
N	39	39	35	13	17	16
Minimum	0.03	0.15	0.10	0.05	0.1	3
Maximum	30.00	2.25	21.00	11.40	6.3	274
Mean	2.82	1.00	4.25	2.31	1.2	64
St.dev	5.39	0.53	4.63	2.95	1.5	74
10%	6.90	1.80	9.18	8.60	3.4	220
50% (median)	0.78	0.95	3.00	1.57	0.7	35
90%	0.09	0.30	0.56	0.05	0.1	4

Bimodal-Felsic/Felsic subclass

	Tonnage (Mt)	Cu %	Zn %	Pb %	Au g/t	Ag g/t
N	68	78	78	66	35	66
Minimum	0.05	0.01	0.01	0.01	0.03	0.1
Maximum	137.3	2.48	17.00	9.30	15.0	253
Mean	6.62	0.75	4.11	1.56	1.3	45
St.dev	19.09	0.59	3.84	1.93	3.0	44
10%	12.87	1.47	9.06	3.34	2.0	106
50% (median)	1.17	0.60	3.07	0.72	0.5	31
90%	0.15	0.12	0.07	0.04	0.1	5

Summary statistics for the siliciclastic-mafic, mafic, bimodal-mafic and bimodal-felsic sub-classes of the VMS deposits are given in the tables above.

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The statistics show that there are clear differences between the subclasses with respect to grades of the elements as well as tonnages. The highest copper grades are found in the mafic and siliciclastic-mafic classes (median values of 1.5 and 1.2 % respectively), whereas the felsic-hosted deposits have less than half of the grade (median value 0.6 %). The highest zinc grades are found in the felsic and bimodal-mafic subclasses (median values 3.1 and 3.0 %, respectively), whereas mafic-hosted deposits only have 1.1 % (median value). The bimodal-mafic class is the richest in lead, gold and silver, whereas the mafic subclass has the lowest grades. With respect to tonnage, the felsic- and mafic-hosted deposits are clearly larger than the other two subclasses (median 1.17 and 1.06 Mt compared to 0.78 Mt, respectively).

The differences between the subclasses are also evident in the cumulative frequency diagrams for tonnage, Cu and Zn in Figure 9, Figure 10 and Figure 11.

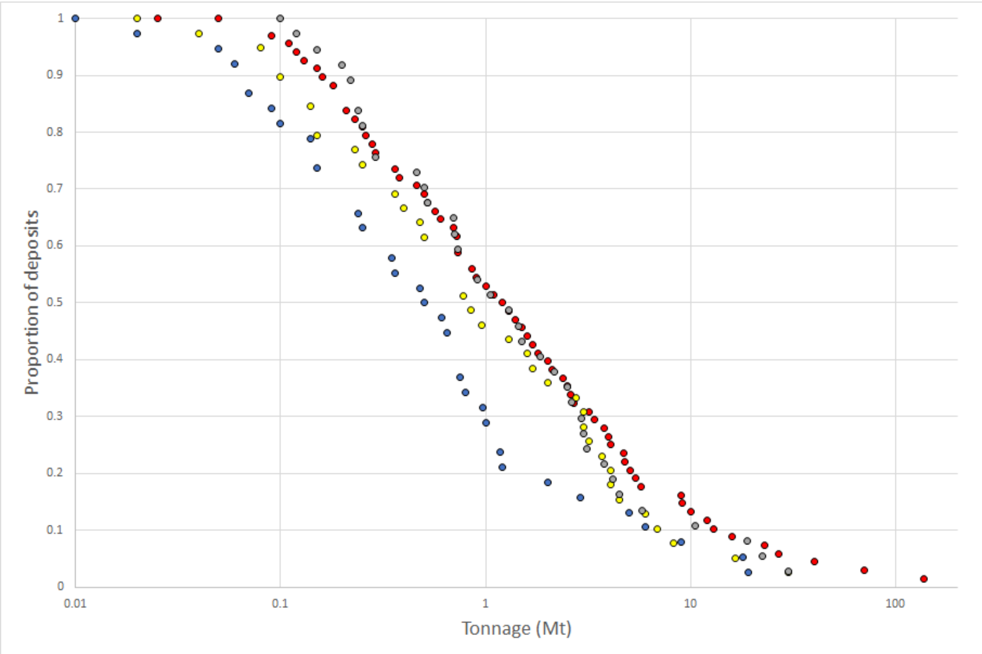

Figure 9: Cumulative frequency of tonnages for VMS deposits in the Caledonian-Appalachian orogen, divided into subclasses. Blue: Siliciclastic-Mafic, Yellow: Bimodal-Mafic, Grey: Mafic, Red: Felsic/Bimodal-Felsic.

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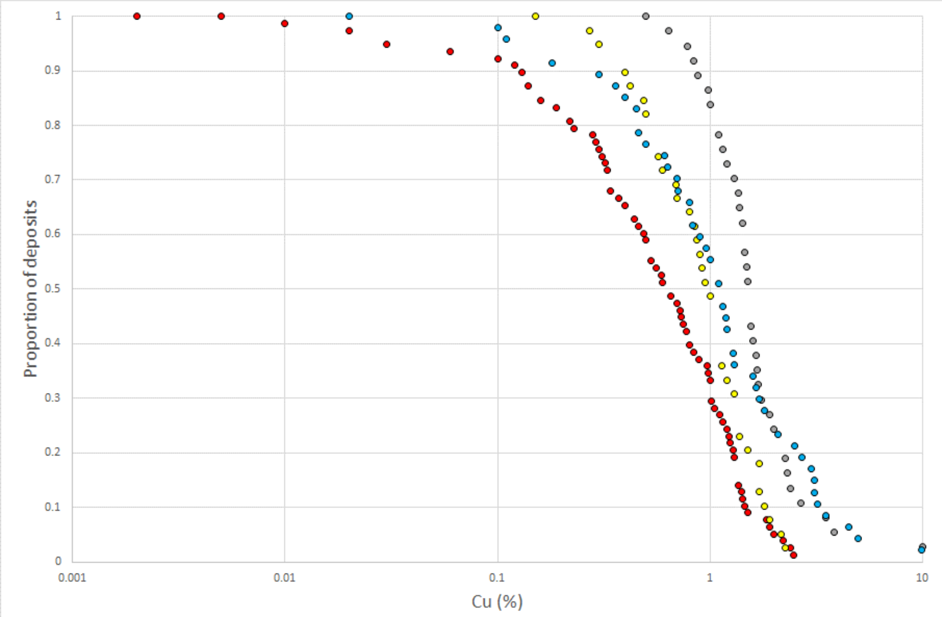

Figure 10: Cumulative frequency of copper grades for VMS deposits in the Caledonian-Appalachian orogen, divided into subclasses. Blue: Siliciclastic-Mafic, Yellow: Bimodal-Mafic, Grey: Mafic, Red: Felsic/Bimodal-Felsic.

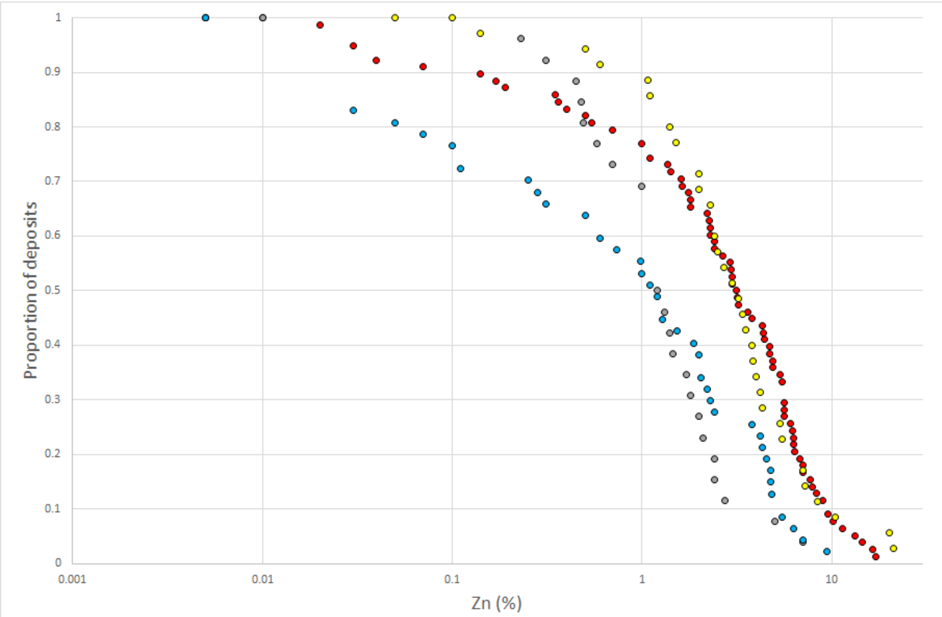

Figure 11: Cumulative frequency of zinc grades for VMS deposits in the Caledonian-Appalachian orogen, divided into subclasses. Blue: Siliciclastic-Mafic, Yellow: Bimodal-Mafic, Grey: Mafic, Red: Felsic/Bimodal-Felsic.

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4.4. Assessment of the Gjersvik tract

Description of the tract

The Gjersvik VMS permissive tract covers an approximately 2-10 km wide and 80 km long area in the central part of Norway, extending from Grong in the SW to Røyrvik in the NE (Figure 12).

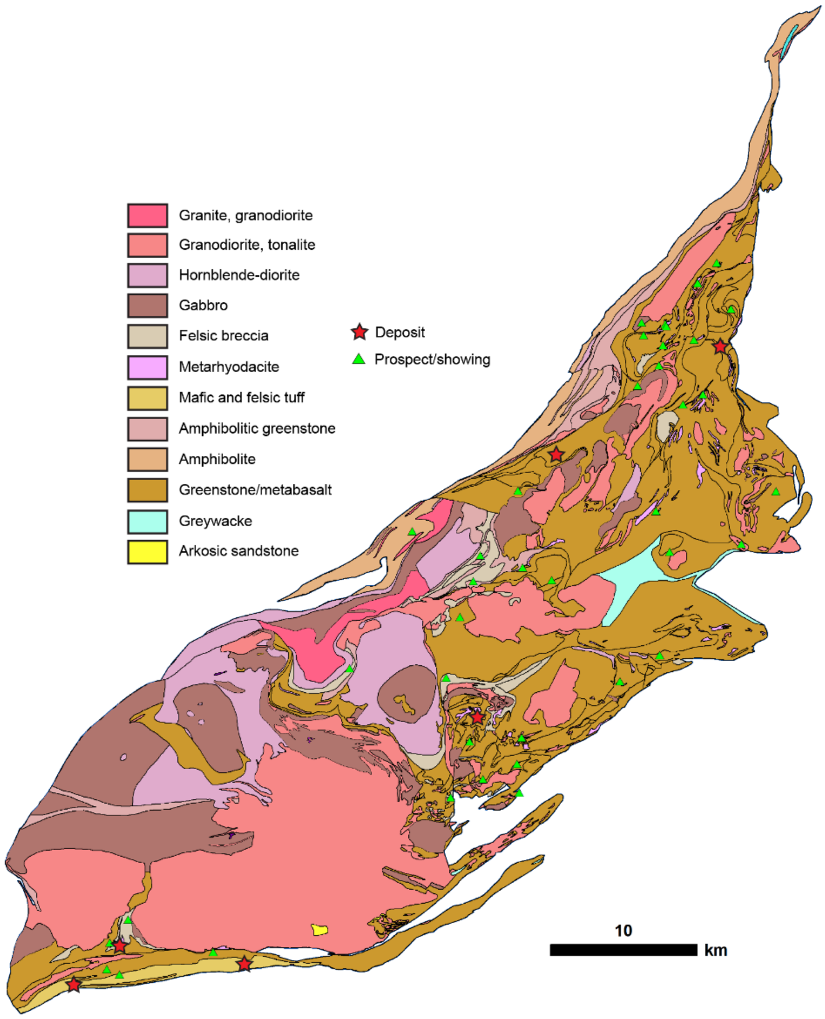

Figure 12: Geology of the Gjersvik tract, based on NGU bedrock database (1:250 000 scale). Known mineralisations (from NGU ore database) are also shown.

The Gjersvik tract is made up of the Early Ordovician Skorovas Complex (SC) which is composed of submarine volcanic and plutonic rocks. It is unconformably overlain by psammitic metasedimentary rocks of the Limingen Group (Figure 13). The volcanic part of the SC, the Bjørkvatnet Formation, is divided into three stratigraphic members (Sandstad et al. 1997; Grenne et al. 2000). The Lower Member consists of a sequence of basaltic lavas and subordinate basaltic andesites. The Middle

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Member comprises strongly fractionated Fe-Ti basalts followed by a heterogeneous unit of feldspar-phyric, low-K rhyodacite flows, basaltic andesites and volcaniclastic rocks. The Upper Member consists of primitive Mg-rich, pillowed and massive basalts, subordinate quartz-phyric volcanic rocks and calcareous tuffites. Geochemical data indicate a subduction affinity for the whole volcanic sequence. The Lower Member can be related to the early stages of ensimatic arc construction, whereas the higher units formed in response to rifting processes within the arc complex.

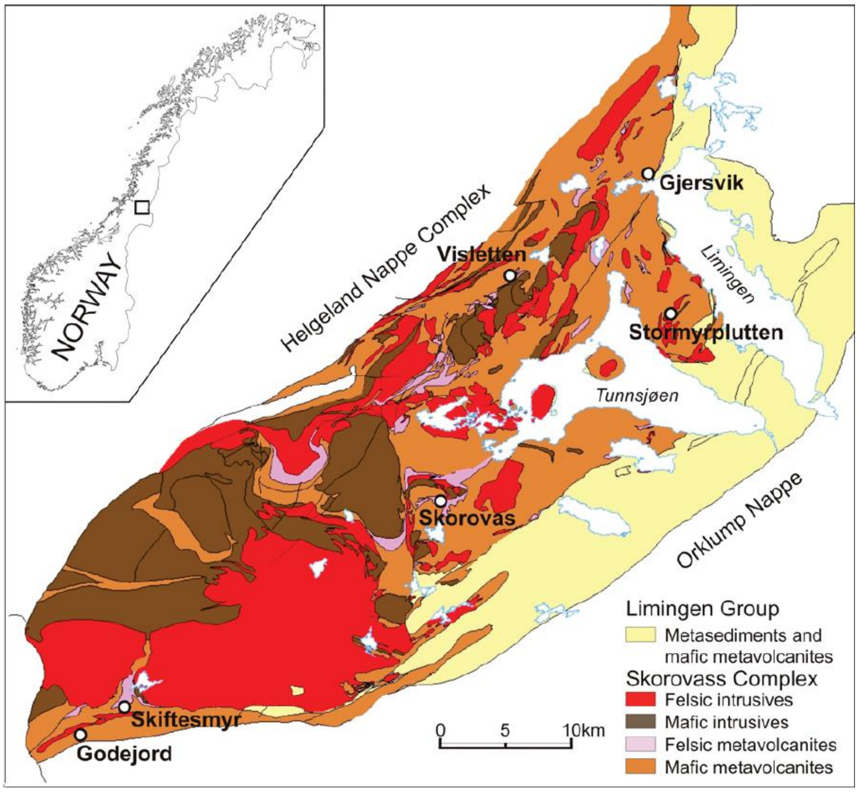

Figure 13: Simplified geological map of the Gjersvik Nappe showing the location of the major VMS deposits and the Stormyrplutten Ni-Cu occurrence (from Sandstad et al., 2012).

Massive sulphides are abundant in the rift-related part of the volcanic succession, particularly in the Middle Member of the SC. The earliest, Cu-Zn dominated ores (e.g., Skorovas, Gjersvik) occur between the Fe-Ti basalts and the overlying low-K rhyodacites. Continuous hydrothermal activity through the Middle Member is manifested by deposits with higher Zn/Cu ratios and Pb contents at higher stratigraphic levels (e.g., Visletten, Godejord), a feature that may be related to the increased felsic magmatic activity with time (Sandstad et al. 1997). Minor gabbro bodies related to the primitive metabasalts of the Upper Member contain massive or disseminated Cu-Ni sulphides with significant PGE+Au enrichment in the Stormyrplutten and Lillefjellklumpen occurrences (Grenne et al. 1999).

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Deposits and prospects in the Gjersvik tract

There are six known deposits within the Gjersvik tract, of which two have been mined in the past, the Skorovas and Gjersvik deposits (Table 2).

Table 2: Deposit data for the Gjersvik tract.

Name	East	North	Total tonnage	Mined	Grade (%)	Reference
Skorovas	409282	7168149	6.9 Mt	5.6 Mt	1.14 Cu, 2.71 Zn	Sandstad et al., 2012
Gjersvik	425772	7193348	1.62 Mt	0.5 Mt	2.15 Cu, 0.50 Zn	Sandstad et al., 2012
Skiftesmyr	384970	7152639	4.07 Mt	-	1.00 Cu, 1.50 Zn	MetalProspecting AS (NI 43-101)
Visletten	414612	7185989	0.78 Mt	-	0.92 Cu, 3.86 Zn	Sandstad et al., 2012
Godejord	381866	7149969	0.25 Mt	-	0.60 Cu, 4.20 Zn	MetalProspecting AS (NI 43-101)
Finnbu	393421	7151359	0.25 Mt	-	0.30 Cu, 3.00 Zn	NGU database

Mt – million metric tons

The Skorovas deposit was in operation from 1952 to 1984 (discovered in 1873), with a total production of 5.6 Mt that until 1976 consisted of pyritic ore. During the final operating years, Cu and Zn were exploited. Remaining in situ reserves at the closure were 1.3 Mt in the 'Southern Orebody' (Reinsbakken 1992). The deposit is about 800–900 m long, 200–300 m wide and, at maximum, 50 m thick and comprises an en-echelon array of closely spaced, elongated, flat-lying massive sulphide lenses. A pronounced zonation in the distribution of Cu and Zn exists. The northernmost part of the deposit is pyrite-dominated and consists of a thick zone of disseminated and veined sulphides within a strongly schistose, chlorite-quartz rich rock which may represent the central, top part of the feeder-zone. The northern, major parts of the Main and East ore bodies are dominantly pyritic and contain only minor amounts of Cu and Zn, but grade southwards into more base metal-rich ores. These ore bodies occur above Fe-Ti rich metabasalts of the Middle Member of the Bjørkvatnet formation and are overlain by differentiated basaltic andesites and andesites. The SE and SW ore bodies are locally Zn-rich and are interpreted as having formed at upper stratigraphic levels, above felsic flows and pyroclastics.

The Gjersvik deposit was discovered in 1909 and mined in the period 1993-1998 (Sandstad et al., 2012). Total reserves were 1.6 Mt at 1.7 % Cu and 1.0 % Zn, and only trace amounts of Pb and precious metals. Production was based on 0.5 Mt grading 2.15 % Cu and 0.60 % Zn as a satellite deposit for the Joma mine. The massive ore zone is up to 8 m thick and consists of a series of sulphide layers or lenses separated by thin chloritic zones. The ore is mainly pyritic and Cu-dominated with varying amounts of pyrrhotite, magnetite, chalcopyrite, and sphalerite in a carbonate-quartz-chlorite gangue. A lens of very Zn-rich pyritic ore (10-20 % Zn) occurs 10–20 m above the main ore.

Massive sulphides at *Skiftesmyr* mainly consist of pyritic Zn-Cu ore, which occurs as layers or a continuous series of ore lenses forming a 2–20-m thick, plate-like orebody overlain by lenses of magnetite-bearing metachert. The main gangue minerals are quartz, chlorite and calcite. Both footwall and hanging-wall rocks are strongly affected by quartz-sericitic, albitic and chloritic alteration with variable amounts of sulphide veins and dissemination. The ore body shows a

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marked lateral zonation, with Cu-dominated ore concentrated in the eastern and upper levels of the ore body and Zn-rich ore in the western parts and at depth. The indicated and inferred resource for the deposit is 4.08 Mt with 1.0 % Cu, 1.5 % Zn, 0.3 g/t Au and 9 g/t Ag with a cut-off grade of 0.5 % Cu (Geovista, 2013). The data for Cu and Zn and tonnage is NI43-101 compliant, while the Au and Ag data are based on extrapolation from previous data.

The *Visletten deposit* comprises a massive ore zone with a thickness of up to 3 m consisting of pyrite with layers rich in sphalerite and subordinate galena, minor chalcopyrite and metachert. Reserves have been calculated at 0.8 Mt with 0.9 % Cu and 3.9 % Zn. Zinc-rich layers carry up to 1 % Pb and are significantly enriched in Ag and Au (up to 90 g/t and 2 g/t, respectively). The massive sulphide ore is underlain by a sequence of basaltic lavas that are extensively chloritised and sulphide-veined below the massive ore level. The stratigraphic hanging wall comprises quartz-phyric felsic flows, overlain by pillow lavas. The distal part of the ore unit is associated with thin beds of magnetite-bearing chert.

The *Godejord deposit* has a 5 to 10 m thick ore zone with massive to banded and disseminated sulphides in a variably tuffaceous, calcareous and cherty host. It occurs in the upper part of a thick sequence of mainly tuffaceous or epiclastic sediments with interlayered felsic effusives. The ore lies stratigraphically on top of a 10 m thick layer of magnetite-bearing chert with local Mn enrichment, and is separated from an overlying basaltic unit by a thin zone of calcareous sediments similar to those below the ore body (Grenne 1995). The richer parts of the laterally extensive Godejord zone have been estimated to contain 0.25 Mt with 0.6 % Cu, 4.2 % Zn, 0.2 % Pb, 15 g/t Ag and 0.4 g/t Au calculated at a cut-off of 1 % Cu equivalent (Grenne & Erichsen 1996).

In addition to the six deposits, there are almost 40 known occurrences, which all have been characterised as bimodal-mafic VMS in the Gjersvik permissive tract. several of these represent distal exhalites They are listed in Table 3, along with mean analytical data from samples in the NGU ore database.

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Table 3: Data for prospects in the Gjersvik tract.

Name	East	North	Host rock	Cu (%)	Zn (%)	Pb (%)	Ag(g/t)	Au (g/t)	N
Furutangvika	427182	7179879	rh-d, bs	0.03-0.09	<0.01-0.02	<0.01	<1	<0.1	4
Kastvika	421652	7172329	bs	0.01-0.03	<0.01-0.01	<0.01	<1-6	<0.1-0.5	3
Rørvatn	423232	7189349	rh-d, bs	<0.01-0.3	0.03-1.6				Core
Selbekkskjerpene	421612	7192008	bs	<0.01	0.02	<0.01	<1	<0.1	11
Stortjern	409472	7179099	rh-d, bs	<0.01-0.02	<0.01-0.08	<0.01	<1	<0.1	5
Langtarmen	412111	7162989	rh-d, bs	0.01-0.02	<0.01-0.01	<0.01	<1	<0.1	5
Havdalstjørna	418952	7170549	bs	<0.01-0.02	<0.01-0.02	<0.01	<1-3	<0.1-0.2	5
Hausvika	414302	7177419	rh-d, bs	0.05	0.02	<0.01	<1	<0.1	13
Pedersen skjerpet	423982	7193738	rh-d, bs	1.50-3.55	0.07-0.14	<0.01	10-18	0.1-0.2	2
Gudfjelløya	422332	7179349	rh-d, bs	<0.01-0.06	<0.01-0.15	<0.01	<1-8	<0.1	4
Blindtarmen	411952	7164929	bs	0.01	0.02	0.01	<1	<0.1	6
Langtjønna	412262	7166719	rh-d, bs	0.01	0.03	<0.01	<1	<0.1	8
Mariafjellet	429532	7183459	bs	0.02	0.24	<0.01	1	<0.1	7
Halvveisberget	421882	7193388	bs	<0.01	0.02	<0.01	<1	<0.1	21
Bjørkvatnet	420572	7194059	rh-d, bs	<0.01-0.06	0.01-0.03	<0.01	<1-1	<0.1	5
Annlifjell	422032	7194818	rh-d, bs	<0.01-0.05	0.02-1.58	<0.01-0.11	<1-11	<0.1-0.9	4
Annlia	422112	7194678	rh-d, bs	0.03	0.05	<0.01	1	<0.1	15
Kirma	424222	7197588	rh-d, bs	0.04	0.06	0.01	9	<0.1	16
Nesåflyin	409631	7163889	bs	0.01	0.03	<0.01	<1	<0.1	8
Småvatnan	408992	7177349	bs	0.07	0.01	<0.01	<1	<0.1	8
Volltjørna	412332	7178269	rh-d, bs	0.12	0.02	<0.01	<1	<0.1	8
Austvatnet	425512	7198989	rh-d, bs	0.38	0.02	<0.01	8	<0.1	13
Bjørkvassdalen Ø	420152	7190619	bs	0.01	0.01	<0.01	<1	<0.1	10
Gjersvikklumpen	424592	7190038	rh-d, bs	0.09	0.29	<0.01	<1	<0.1	13
Holmmo	421402	7182109	rh-d, bs	0.01	0.03	<0.01	<1	<0.1	12
Litlfjellet	426492	7195839	rh-d, bs	0.06	0.02	<0.01	<1	<0.1	22
Orvasselv	420432	7194923	rh-d, bs	0.04	0.01	<0.01	<1	<0.1	8
Finnkrudomma	407451	7162649	rh-d, bs	0.02	0.02	<0.01	1	<0.1	21
Øv. Nesåvatnet	408732	7166449	rh-d, bs	0.79	0.05	<0.01	2	<0.1	15
Stor-Skorovatn	407157	7170794	rh-d, bs	0.05	<0.01	<0.01	3	<0.1	6
Grønndalselv	400572	7171419	rh-d, bs	0.21	1.10	0.02	2	<0.1	6
Tunnsjøflyin	408082	7174899	rh-d, bs	0.03	0.02	<0.01	<1	<0.1	21
Lille Tromselv	412012	7183499	rhy, bs	0.31	3.68	0.89	66	0.4	15
Tunnsjødalplassen	404852	7180739	rh-d, bs	<0.01-0.03	<0.01-0.22	<0.01	<1	<0.1	4
Broka	384981	7150599	vcs, bs	0.02	0.07	<0.01	<1	<0.1	6
Angeltjernhøgda	384102	7150959	vcs, bs	0.02	0.13	<0.01	<1	<0.1	8
Sandtjern	384312	7152759	rh-d, bs	0.03	0.05	<0.01	<1	<0.1	9
Rognhaugen	391331	7152144	rh-d, bs	<0.01	0.01	<0.01	<1	<0.1	7
Møklevatnet	385561	7154324	rh-d, bs	0.05	0.06	<0.01	<1	<0.1	16

Mean values calculated for occurrences with more than 5 samples, range shown for occurrences with 5 samples or less.
rh-d: rhyodacite, bs: basalt, rhy: rhyolite, vcs: volcaniclastic sediment. N: number of samples.

Exploration data

The geology of the tract is mapped in 1:50 000 to 1:250 000 scale, as well as more detailed mapping in areas around the deposits and some of the mineralisations. For the purpose of testing of the MAP software, the geology from the NGU bedrock database has been used (http://geo.ngu.no/kart/berggrunn_mobil/).

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Geochemistry including soil and stream sediment data, cover most of the area. All the data is downloadable from the NGU geochemistry database (http://geo.ngu.no/kart/geokjemi_mobil/). The stream sediment data have been used in this test.

Geophysics, including high resolution airborne magnetometry, radiometry and electromagnetics, cover most of the tract. Detailed ground geophysical measurements have also been carried out in major parts of the area. In this testing only airborne magnetometry and electromagnetics have been used. The data was downloaded from the geophysics database at NGU (https://geo.ngu.no/geoscienceportalopen/search)

Modelling by the MAP Wizard

For the descriptive model, the VMS model was used (see section 3) and for the grade-tonnage model, data for the VMS bimodal-mafic subtype was used (see section 4.3 and data set in the appendix).

Grade-Tonnage model

1. Grade summary
Summary comparison of the pdf (probability density functions) representing the grades and the actual grades in the grade and tonnage model (Gatm) for the bimodal-mafic subclass of VMS deposits.

Pdf type: normal
Pdf is not truncated.
Number of discovered deposits in the grade and tonnage model: 35
Number of resources: 2

Quantiles (reported in percent)
Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

	Component Cu		Component Zn		Component gangue	
	Gatm	Pdf	Gatm	Pdf	Gatm	Pdf
Minimum	0.150	0.0309	0.10	0.00895	78.5	11.1
0.25 quantile	0.585	0.5780	1.50	1.20000	94.2	93.2
Median	1.000	0.8830	3.00	2.61000	96.2	96.2
0.75 quantile	1.340	1.3500	4.80	5.61000	97.2	97.8
Maximum	2.250	16.4000	21.00	88.80000	99.6	99.8

Compositional mean (reported in percent).		
	Gatm	Pdf
Cu	0.903	0.903
Zn	2.620	2.620
gangue	96.500	96.500

Composite variation matrix			
	Cu	Zn	gangue
Cu	0.000	1.65	0.401
Zn	1.660	0.00	1.390
gangue	0.401	1.39	0.000

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.
The composite variation matrix has two parts: its upper triangle and its lower triangle. The upper triangle is the upper triangle of the variation matrix for the actual grades in the grade and tonnage model. The lower triangle is the lower triangle of the variation matrix for the pdf that the represents the grades. Thus, corresponding elements in the upper and lower triangles should be compared to one another.

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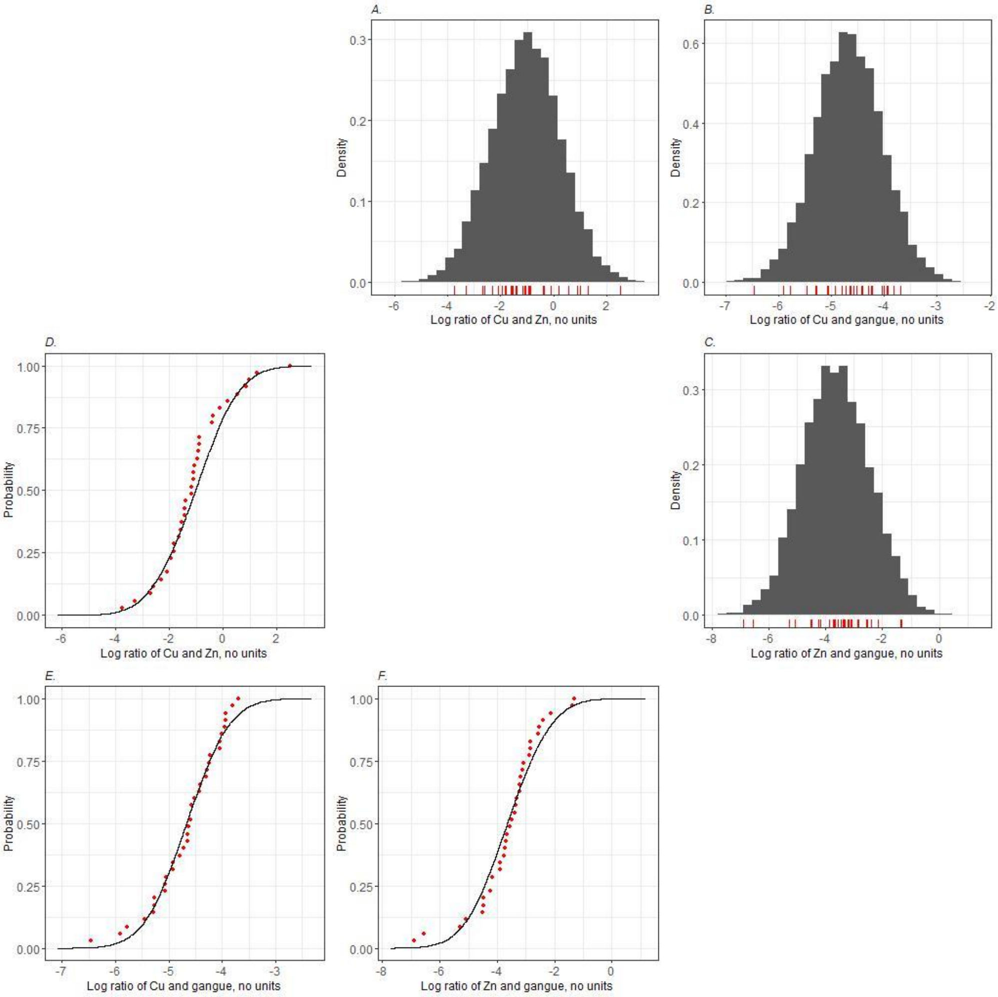

Figure 14: Histograms and cumulative distribution functions, calculated from the probability density function representing the grades. In A-C, vertical red lines (bottom) represent the log-ratios calculated from the grade-tonnage model. in D-F, the red dots are empirical distribution functions for the log-ratios calculated from the grade-tonnage model.

2. Tonnage summary

Summary comparison of the pdf representing the tonnage and the actual tonnages in the model for VMS deposits of the bimodal-mafic subclass.

Pdf type: normal
Pdf is not truncated.
Number of discovered deposits in the model: 35
Deviance = -10.4137

The left table pertains to the log-transformed tonnages. Column Gatm refers to the actual tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

The right table pertains to the (untransformed) tonnages. Column Gatm refers to the tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

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	Gatm	Pdf
Minimum	10.10	5.00
0.25 quantile	12.40	12.50
Median	13.60	13.70
0.75 quantile	15.10	14.80
Maximum	17.20	21.90
Mean	13.70	13.70
St. deviation	1.77	1.77

	Gatm	Pdf
Minimum	25 000	149
0.25 quantile	240 000	257 000
Median	780 000	851 000
0.75 quantile	3 470 000	2 810 000
Maximum	30 000 000	3 220 000 000
Mean	3 070 000	4 080 000
St. deviation	5 720 000	18 200 000

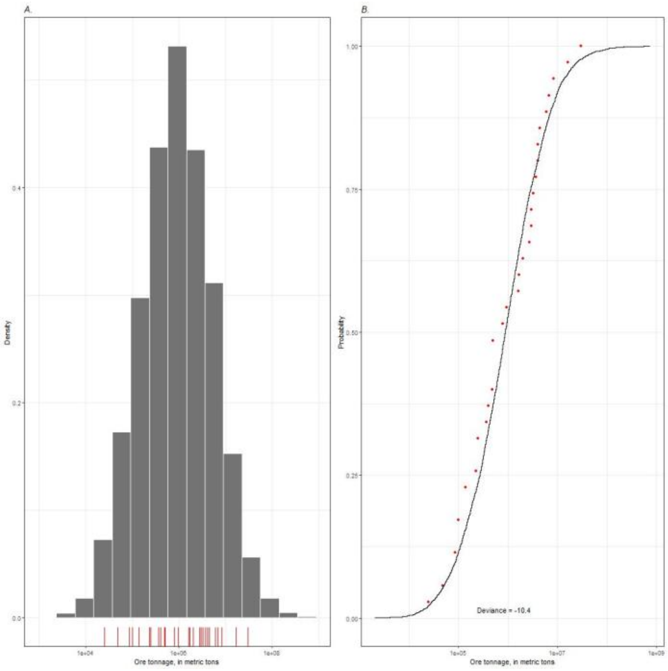

Figure 15: A) Probability density function that represents the ore tonnage in an undiscovered deposit. Vertical lines at the bottom represent the ore tonnages from the grade-tonnage model. B) Corresponding cumulative distribution function (solid line). The red dots are the empirical cumulative distribution function for the ore tonnages from the grade-tonnage model.

Tract delineation

The Gjersvik tract is bounded by the extent of volcanic rocks belonging to Skorovass Complex in the Gjersvik Nappe in the Upper Allochthon of the Central-Norwegian Caledonides. The volcanic rocks are of early Ordovician age, and are bimodal in composition, ranging from basalt to rhyodacite. The presence of bimodal-mafic VMS deposits and occurrences, detailed geological mapping, detailed geophysics and geochemistry were used to define and delineate the tract area (Figure 14, Figure 15, Figure 16).

The fuzzy memberships were calculated using the overlay functions toolbox in ArcGIS and the fuzzified data were then run through the Tract delineation tool in MAP Wizard (Figure 17). The result from the process is shown in Figure 18.

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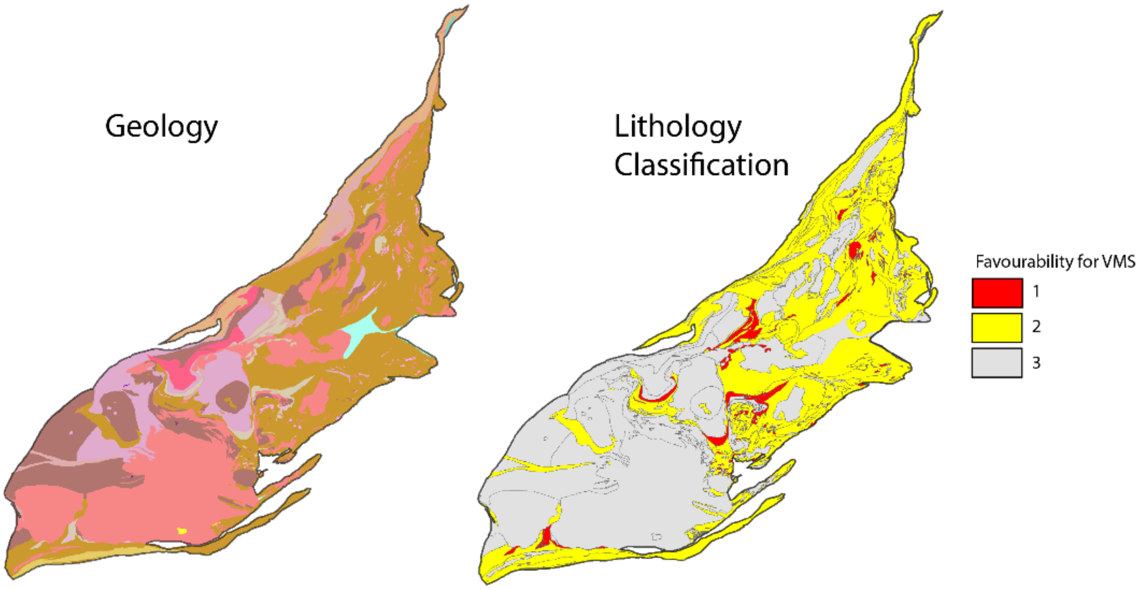

Figure 14: Classification of lithologies (right) in the Gjersvik tract based on the geology (left). Legend for geology, see Figure 12. In the classification, red (number 1) is most favourable to host VMS deposits, whereas grey (number 3) is least favourable.

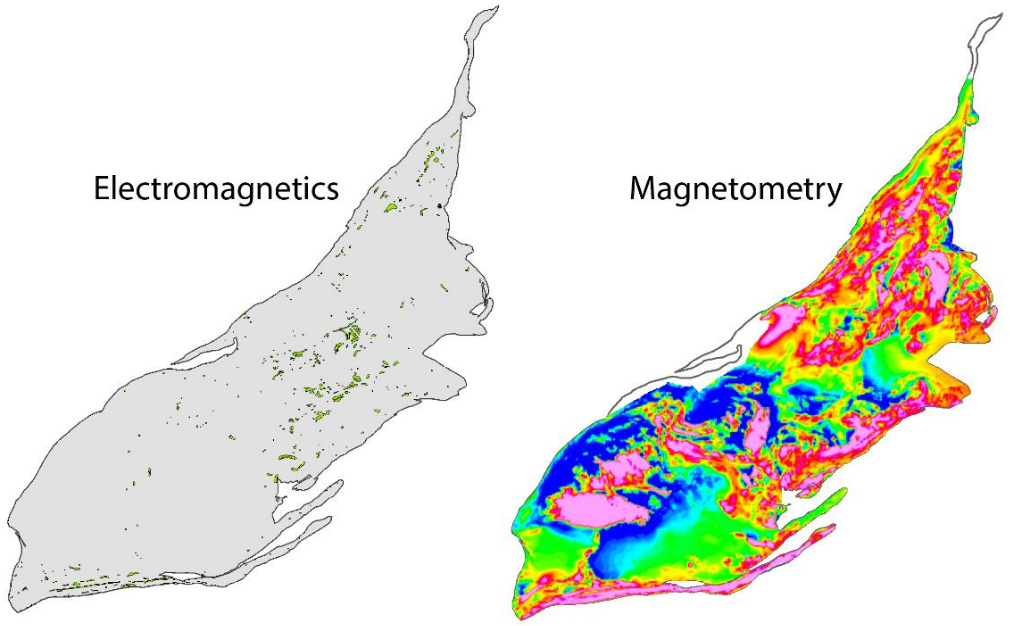

Figure 15: Geophysical data for the Gjersvik tract.

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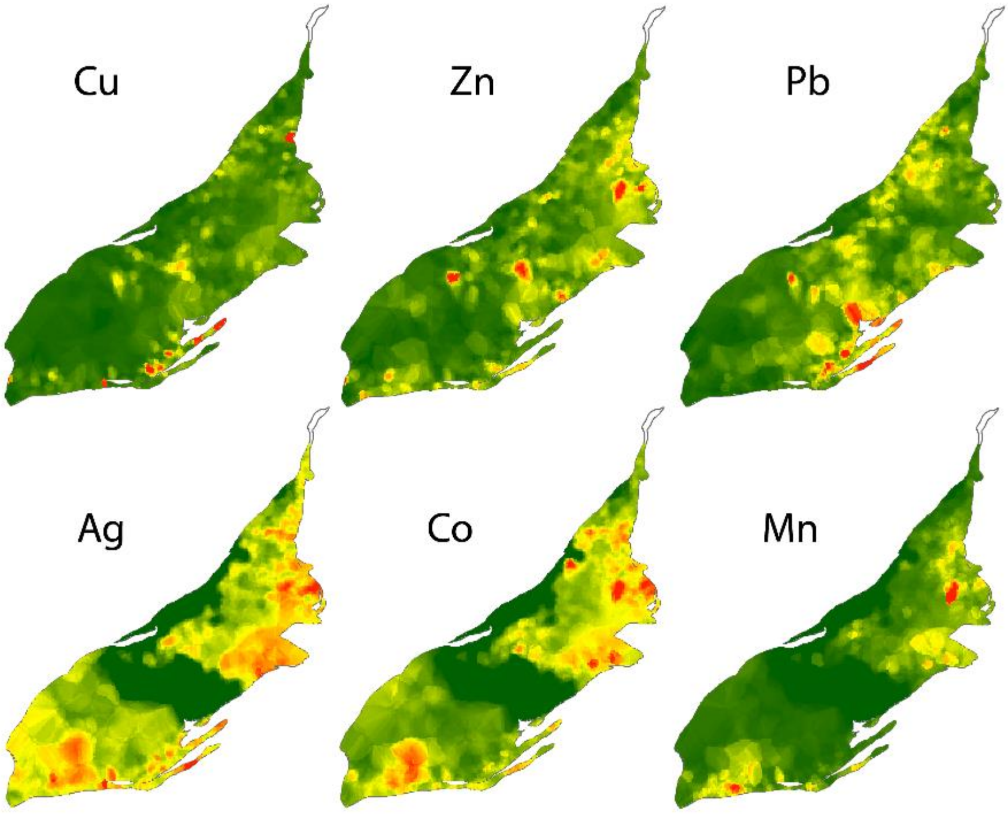

Figure 16: Geochemistry for the Gjersvik tract. The maps show the kriging of stream sediment data, and red represents the highest values and dark green the lowest.

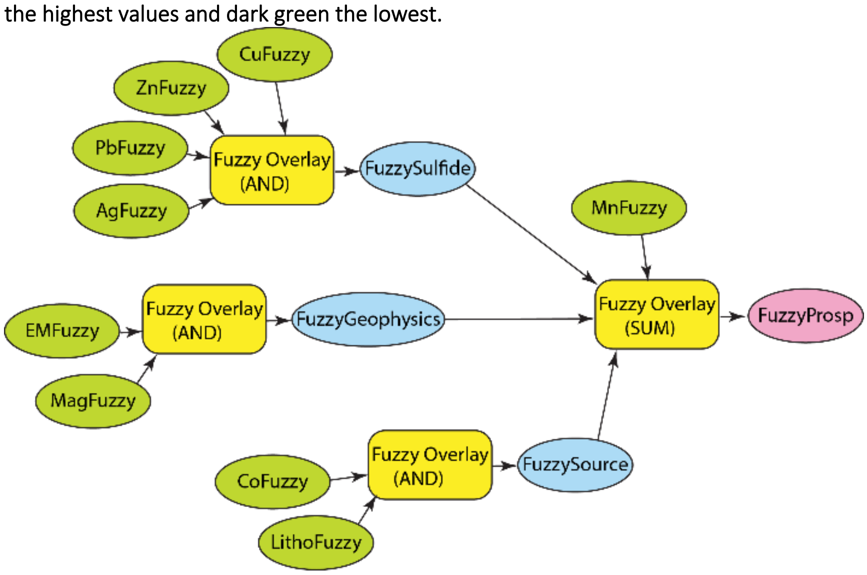

Figure 17: The workflow of the Fuzzy logic mineral potential mapping for the Gjersvik tract.

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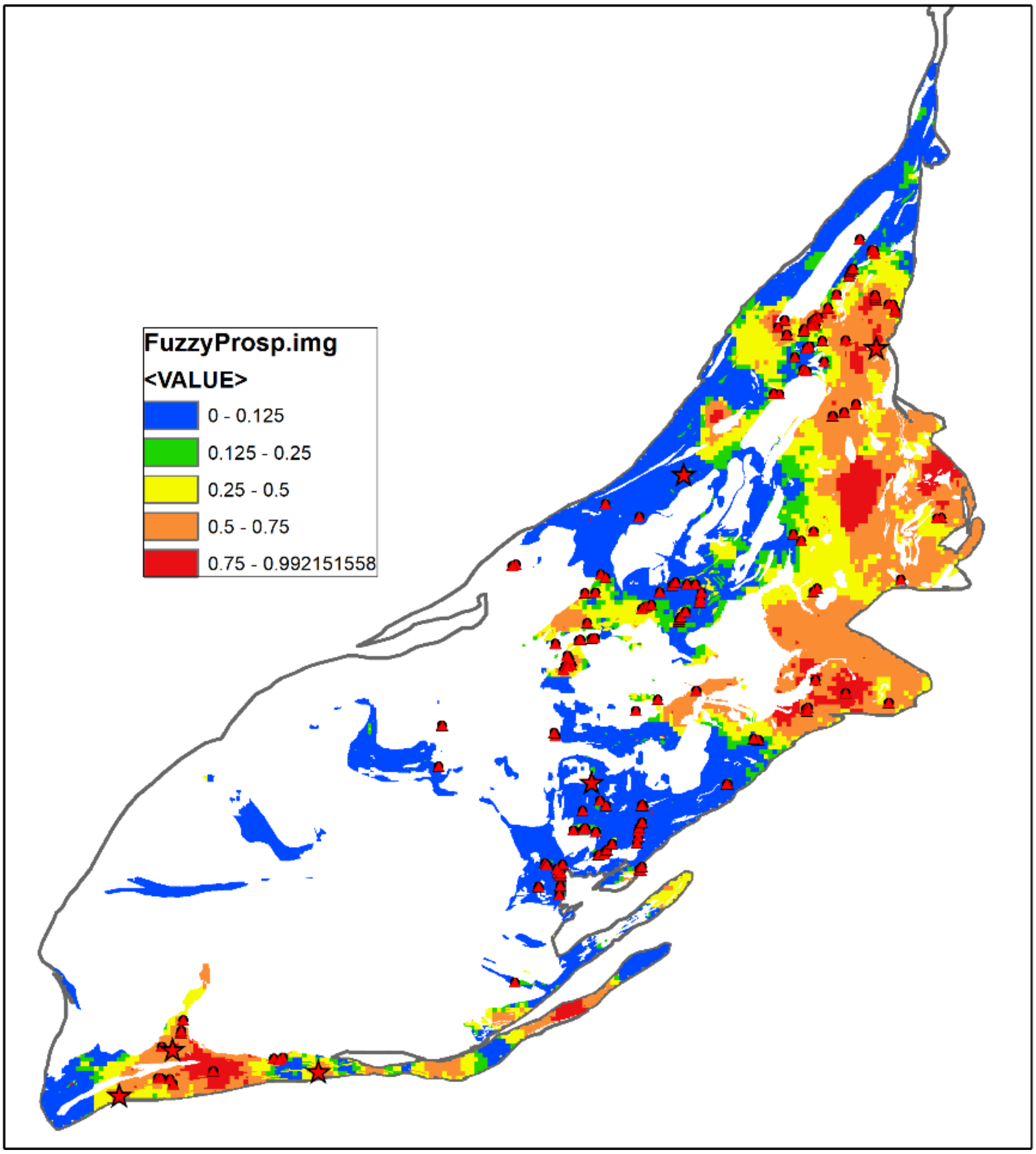

Figure 18: The resulting classification raster from the tract delineation tool in the MAP Wizard. Yellow to red is most favourable and blue least favourable for VMS deposits. White areas represent areas with intrusions later than (postgenetic) VMS formation. Deposits (stars) and prospects (triangles) are shown on top.

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Undiscovered deposits

1. Deposit density model

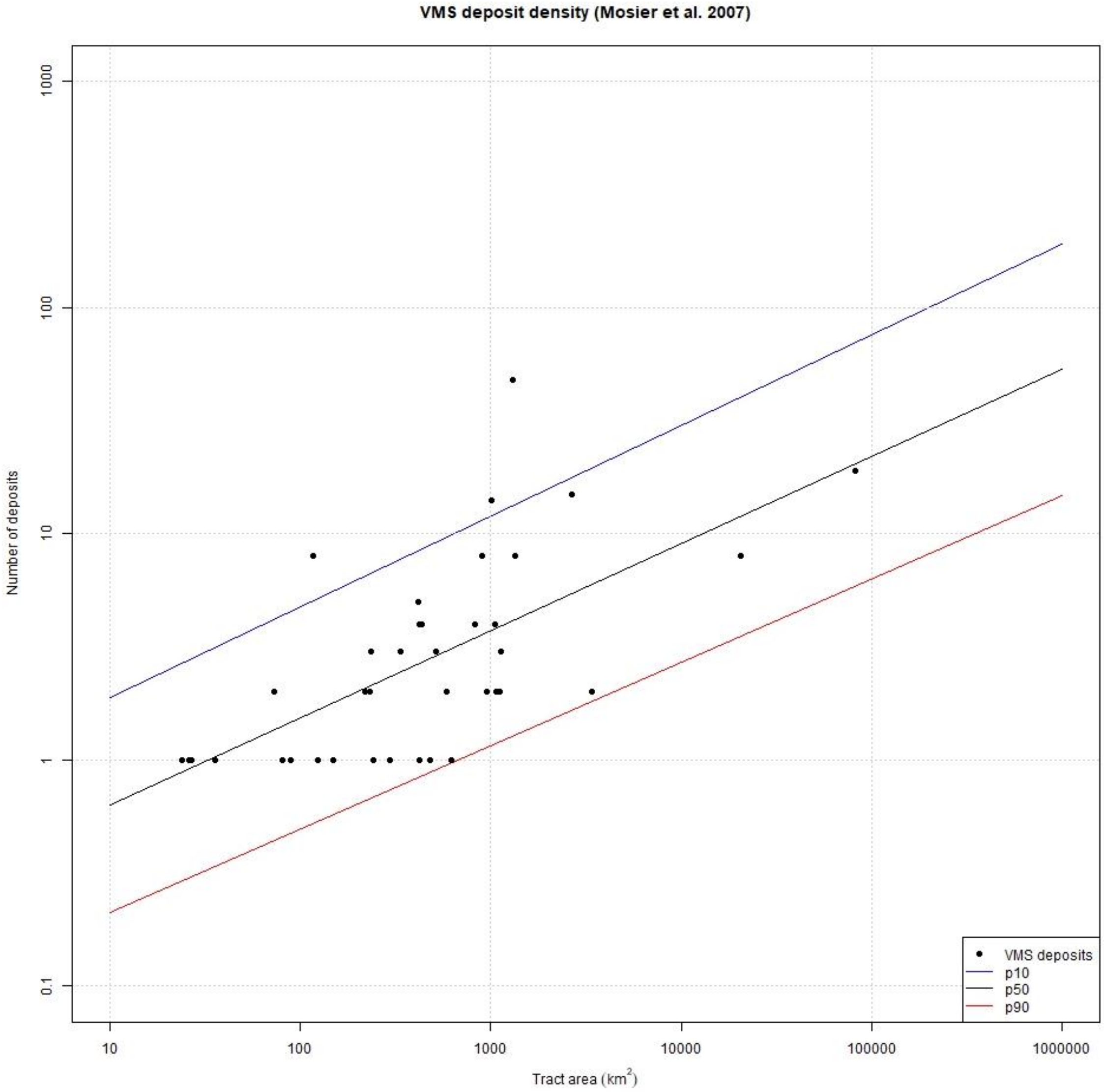

Figure 19: Plot of the VMS deposit density by Mosier et al. (2007).

Excluding the intrusives, which are postgenetic to the VMS deposits (see above), the Gjersvik tract has an area of 564 km^2, which based on the VMS deposit density model by Mosier et al. (2007, Figure 19) gives a probability of N90: 0 deposits, N50: 1 deposit, N10: 3 deposits.

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2. Negative binomial function and expert data

Expert	N90	N50	N10
MST	1	2	4
JSS	2	3	6
KR	1	2	5
STB	1	2	4
OO	1	6	10
MS	0	2	5
TB	1	2	8
KSU	3	6	12
KSA	1	2	4
AH	2	4	7
TG	3	6	12
BK	1	3	6
HS	0	2	4

Summary of pmf, number of undiscovered deposits	
Type	NegBinomial
Mean	2.55533
Variance	2.54817
St. Dev.	1.5963
Mode	2
Smallest N deposits in pmf	0
Largest N deposits in pmf	9
Inform. entropy	1.84229

Expert estimates of deposits in the Gjersvik tract at 0.90, 0.50 and 0.10 probability and the resulting summary statistics for the probability mass function using the negative binomial option.

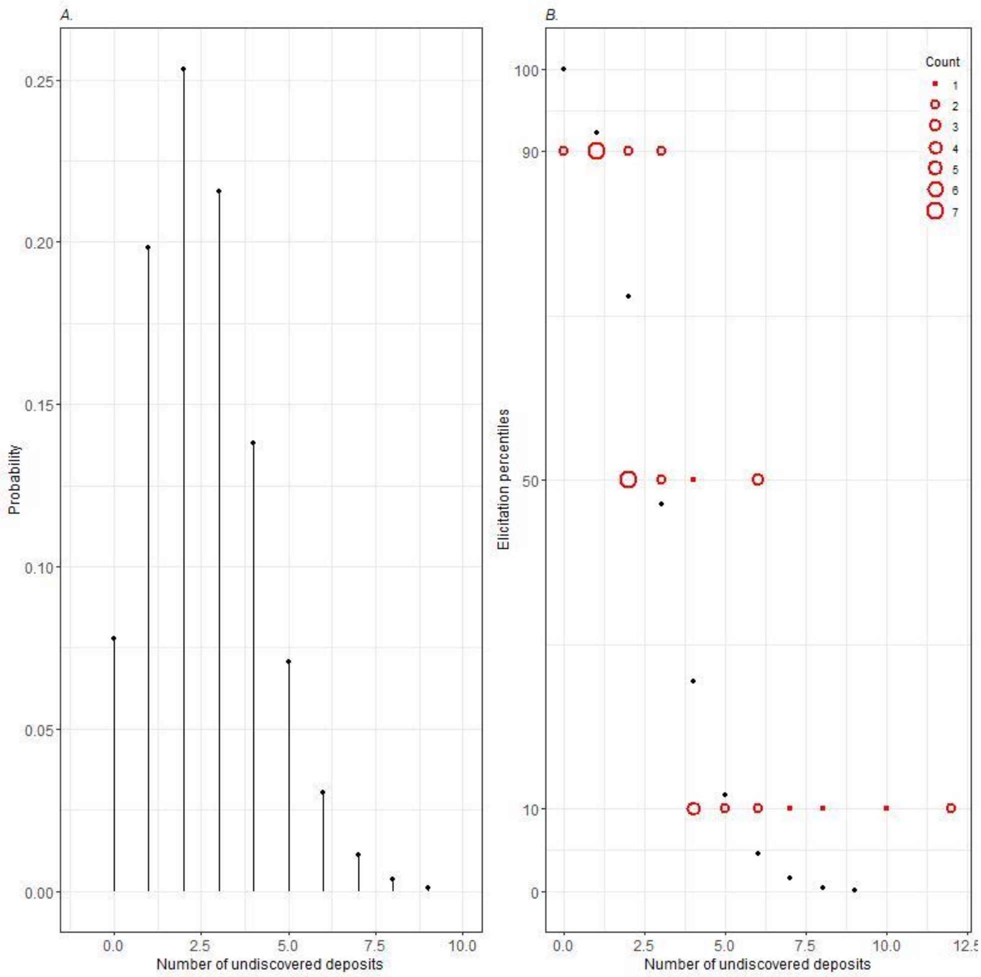

Figure 20 (left): Plot of the estimated probability mass function (pmf) using the negative binomial option. (Right): The corresponding cumulative distribution function with the expert estimates (red circles).

Monte Carlo Simulation with Caledonian VMS Bimodal-Mafic Grade-Tonnage model

Summary of the pdf for the total ore and resource tonnages in all undiscovered deposits within the permissive tract.

	0.05q	0.1q	0.25q	0.5q	0.75q	0.9q	0.95q	Mean	P (0)	P(>mean)
Ore	0	0.106	0.938	3.61	10.2	23.7	39.3	10.5	0.0738	0.243
Cu	0	0.0008	0.008	0.033	0.099	0.249	0.432	0.112	0.0738	0.226
Zn	0	0.0018	0.023	0.108	0.365	1.020	1.810	0.476	0.0738	0.201

Explanation

" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix			
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn
Ore	10.5	10.4	Ore	30.1	29.8	Ore	NA	0.772	0.588
Cu	0.112	0.111	Cu	0.387	0.379	Cu	0.827	NA	0.538
Zn	0.476	0.480	Zn	2.010	2.250	Zn	0.642	0.503	NA

Explanation

1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.
2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

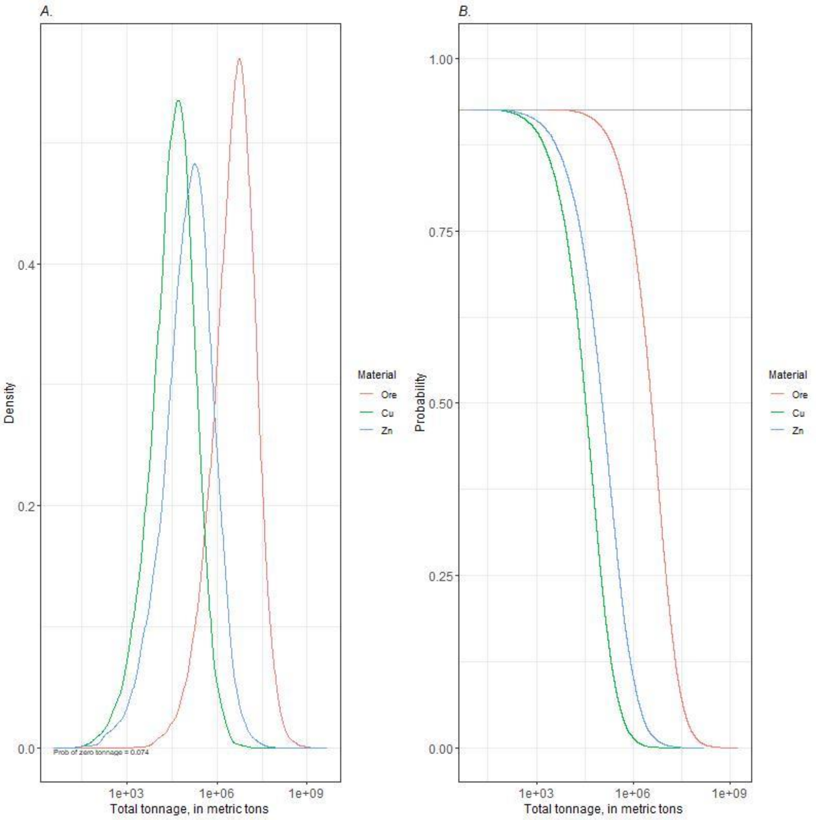

Figure 21: Plots of A: univariate marginal probability density functions and B: cumulative distribution functions for total ore Cu and Zn tonnages in the undiscovered deposits.

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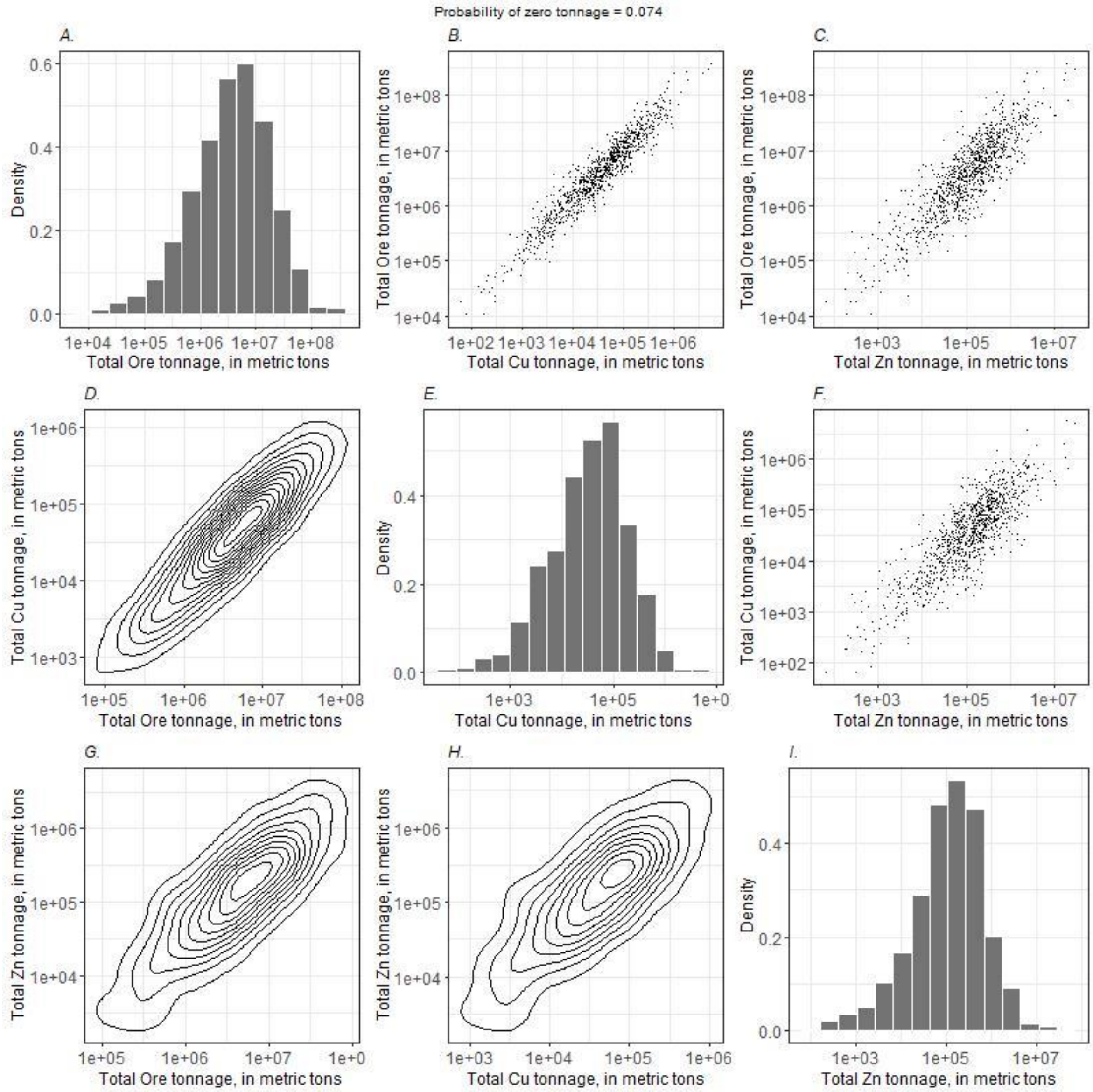

Figure 22: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

Economic Filter

The Economic filter tool estimates the proportion of the total estimated undiscovered resource that can be considered to be economically viable for mining. The tool applies simple engineering cost models to estimate the economic resource, and it is based on the USGS RAEF (Resource Assessment Economic Filter) code (Shapiro & Robinson 2019).

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The Economic filter tool RAEF process allows the same run options as the USGS RAEF software: a) Batch run using preset parameter file, b) interactive run using GUI (Graphical User Interface) input of parameters and c) empirical mode run.

Input data for the filtering using interactive run (ref. Shapiro & Robinson 2019):
Tract area: Gjersvik Tract 564 km^2
Simulated Deposits file: Monte Carlo Simulation Gjersvik
Depth Intervals: 1; 0 - 1000 m and fraction 1
Deposit Type: Flat-bedded/stratiform
Mine method: based on depth to the top of the deposit, if depth >= 61m: Room and Pillar, if depth < 61m: Open Pit
Mill type: 1 – Product flotation
Days of operation: 350 days
Marshall-Swift Cost updating index (MSC): 1.26
Investment rate of return: 0.15 (15 %)
Cap cost inflation factor: 1
Operating cost inflation factor: 1
CV_Cu, MRR_Cu: 3813.958, 0.91 (Commodity Value in 2008$/t, Metallurgical Recovery rate 91%)
CV_Zn, MRR_Zn: 1851.864, 0.9 (Commodity Value in 2008$/t, Metallurgical Recovery rate 90 %)
Waste management options not chosen

Results:

Table 4: Summary statistics for in-ground contained resources and recovered resources (in Mt):

	means	min-max	median	std	P90	P70	P30	P10	Prob>=mean
Ore	10.505	0-1802	3.613	30.110	0.106	1.318	8.188	23.710	0.24325
Cu_con	0.112	0-29	0.033	0.387	0.001	0.012	0.079	0.249	0.22645
Zn con	0.476	0-158	0.108	2.007	0.002	0.034	0.284	1.020	0.2009
Cu rec	0.074	0-22	0.010	0.301	0	0	0.043	0.175	0.214
Zn rec	0.343	0-121	0.054	1.538	0	0	0.189	0.751	0.19855
NPV_tr	2.1e08	0-4.6e10	2.4e07	7.6e08	0	0	1.1e08	5.2e08	0.2122

Table 4 shows statistics for the deposit ore tonnage in million metric tons (Mt), contained in-ground mineral resource tonnage (Cu_con, Zn_Con, in Mt), recovered mineral resource tonnage (Cu_rec, Zn_rec, in Mt) and net present value of the tract (NPV_tr) in 2008$. The net present value pr km^2 is shown below the table; 376657 $(2008)/km^2.

Table 5: Estimates of mean contained and recovered resources (in Mt) by commodity for the user-defined depth intervals (in Mt):

Depth interval	Cu_con_means	Cu_rec_means	Zn_con_means	Zn_rec_means	ProbOfZero
0-1000 m	0.112	0.074	0.476	0.343	0.6136

For the chosen depth interval 0-1000 m, Table 5 lists the mean statistics for the contained and recovered resources of Cu and Zn in million tons in the Gjersvik tract.

The Economic Filter generates two graphs that show estimated ore deposit cutoff grade and recovered ore value as a function of ore tonnage, mine type, and deposit depth. In Figure 23, cutoff grade is expressed as copper equivalent grade (CuEQ%); in Figure 24, cutoff grade is expressed as ore value (in dollars per ton) based on the metallurgical recovery.

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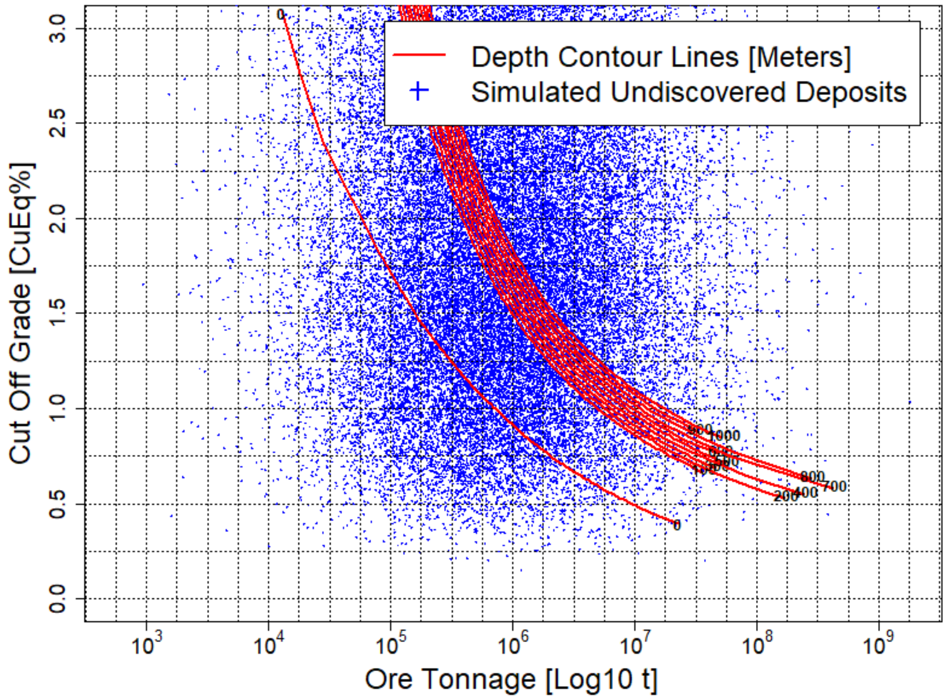

Figure 23: Copper equivalent (CuEQ%) grade/tonnage plot with cutoff grade versus deposit tonnage as a function of depth to top of the deposit in meters.

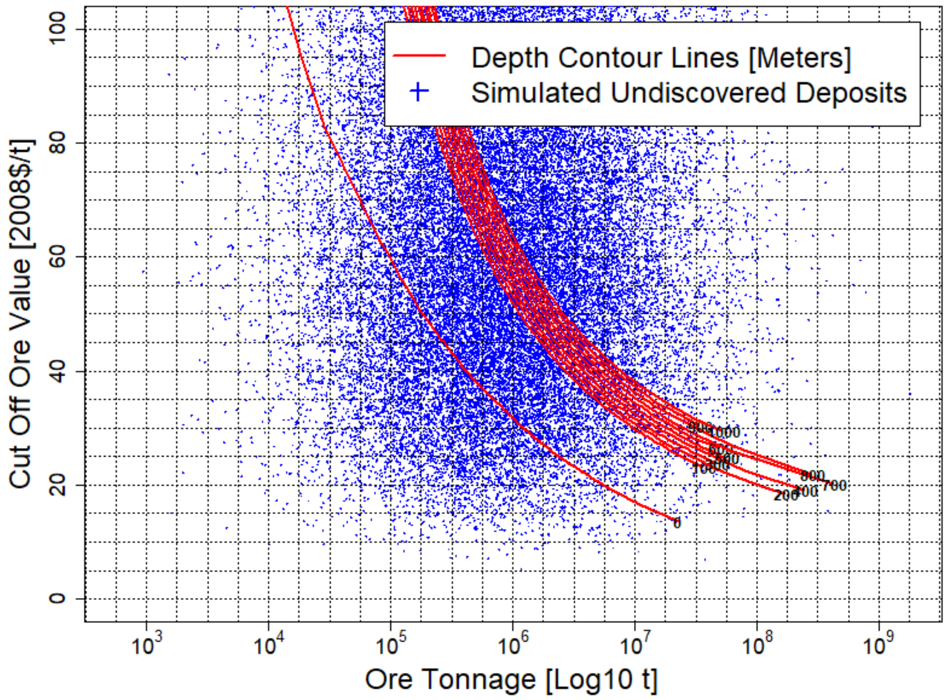

Figure 24: Ore value/tonnage plot with cutoff ore value versus deposit tonnage as a function of depth to top of the deposit in meters.

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Summary of the modelling for the Gjersvik tract

Descriptive Model: VMS

Grade-Tonnage Model for Bimodal-Mafic VMS class: Mean (pdf): 0.90 % Cu, 2.62 % Zn, 3.07 Mt; Median (pdf): 0.88 % Cu, 2.61 % Zn, 0.851 Mt

Tract Delineation: Volcanic rocks in the Skorovass complex, Gjersvik Nappe, area 564 km^2

Undiscovered deposits: VMS deposit density model gives 0 deposits @ N90, 1 deposit @ N50, 3 deposits @ N10. Expert data and negative binomial function: mean number of undiscovered deposits are 2.6

Monte Carlo Simulation – ore and resource tonnages in the undiscovered deposits: (mean) 10.5 Mt ore, 0.112 Mt Cu, 0.476 Mt Zn, (median) 3.61 Mt ore, 0.033 Mt Cu, 0.108 Mt Zn

Economic Filter (commodity value in 2008$/ton): mean value of tract 210 mill. $ (median 24 mill $), mean contained Cu 112 000 t and recovered Cu 74 000 t, mean contained Zn 476 000 t and recovered Zn 343 000 t.

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4.5. Assessment of the Joma Tract

Description of the tract

The Joma VMS permissive tract covers an approximately 2-5 km wide and 100 km long area in the central part of Norway, extending from Tunnsjøen in the south to the northeast end of Namsvatnet in the north. The tract has an area of 290 km2 and has the shape of a double-folded S (Figure 25).

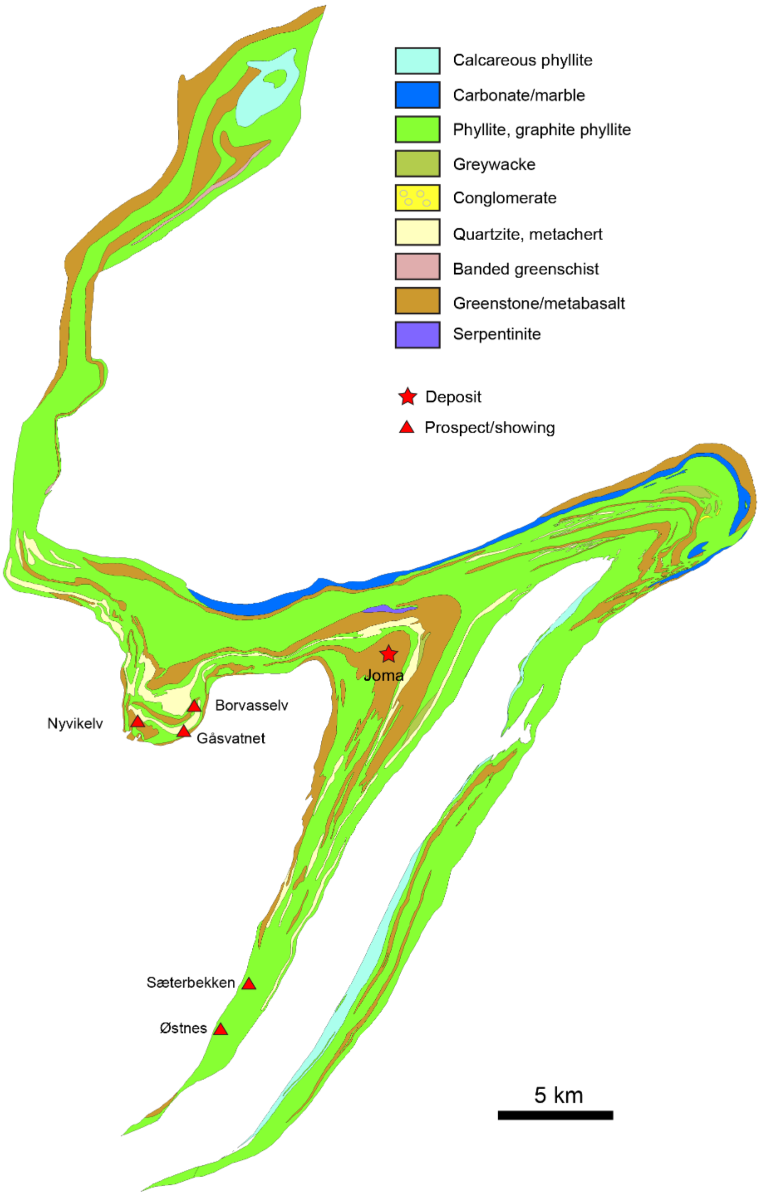

Figure 25: The geology of the Joma permissible tract, based on data from the NGU and SGU bedrock databases. Known mineralisations (from NGU ore database) are also shown.

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The Joma tract is defined by the Røyrvik Group, consisting of greenstones/mafic volcanics, underlain by recrystallised ribbon chert and graphitic phyllites, which again sit on a thick sequence of quartz and calcareous phyllites. The greenstones are interpreted as having formed in an ocean island, probably in an off-axis setting. The rock sequence is structurally overturned and deformed by three phases of deformation related to the nappe emplacement (Reinsbakken 1986, Odling 1988).

The Remdalen group, defined by Zachrisson (1964, 1986a) in Sweden, is correlated with the Røyrvik group and the Bjurälv limestone in the Leipikvattnet nappe (Stephens 1986a). It consists of a lower part of graphitic quartz phyllite intercalated with greenschist, and an upper part with quartzite and quartzite conglomerate interlayered with graphitic phyllite. Marble and quartz porphyry are subordinate components. Geochemical results suggest an oceanic within-plate setting for the mafic rocks (Stephens 1980, Stephens et al. 1985). Parts of the Remdalen group is included in the Joma tract.

Deposits and prospects

Joma is the only known deposit within the tract. The deposit has a total tonnage of 22.5 Mt, of which 11.453 Mt was mined in the period 1972-1998 containing 1.49 % Cu and 1.45 % Zn (Sandstad et al., 2012, Table 6).

Table 6: Deposit data for the Joma tract.

Name	east	north	Total tonnage	Mined	Grade (%)	Reference
Joma	447130	7192549	22.5 Mt	11.453 Mt	1.49 Cu, 1.45 Zn	Sandstad & Hallberg 2012

The massive sulphide deposit occurs at the interface between an older volcanic-intrusive complex and a younger volcanic-volcaniclastic sequence, which show WPB and MORB affinities, respectively. The feeder zone to the massive ore comprises extensive albitisation, chloritization and quartz-sericite alteration associated with sulphide dissemination and stockwork veining.

A general sulphide stratigraphy shows compositional changes from a thin Cu-rich (chalcopyrite-pyrrhotite) layer at the base, thinning away from the feeder zone and intercalated with numerous thin layers of magnetite, chlorite schist and albitite, and overlain by massive pyrite. At one flank of the ore body, the feeder zone mineralisation is overlain by Zn-rich pyritic ore. The most Cu-rich ore is a tectonic breccia, which contains fragments of quartz, carbonate, pyrite and magnetite in a chalcopyrite-pyrrhotite matrix. Primary sulphide-breccia ore types also exist, and a palinspastic reconstruction of the Joma deposit suggests that the massive sulphides were deposited in a submarine environment, on top and adjacent to a major growth fault (Reinsbakken 1986).

In addition to the Joma deposits, there are 5 known occurrences, which all have been characterised as mafic VMS in the Joma permissive tract. They are listed in Table 7, along with mean or range in analytical data from samples in the NGU ore database.

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Table 7: Data for prospects in the Joma tract

Name	east	north	Host rock	Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)	N
Borvasselv	438686	7190243	bs, phyl	2.03	1.97	0.05	50	0.2	15
Østnes	439831	7176274	bs, phyl	0.21	0.41	0.08	10	0.4	13
Sæterbekken	441061	7178248	bs, phyl	0.02-0.05	0.03-0.08	<0.01-0.02	1-2	<0.1	2
Gåsvatnet	438231	7189158	phyl	<0.01	<0.01-0.02	<0.01	<0.1	<0.1	2
Nyvikelv	436241	7189598	tuf,phyl	<0.01-0.03	0.01-0.07	<0.01	<1	<0.1	4

Mean values calculated for occurrences with more than 5 samples, range shown for occurrences with 5 samples or less.
bs: basalt, phyl: phyllite, ch: chert, tuf: tuffite. N: number of samples.

Exploration data

The geology in the tract is mapped in 1:50 000 and 1:250 000 scale, as well as more detailed in the areas around the Joma deposit. For the purpose of this assessment, the geology from the NGU and SGU databases has been used.

Geophysics including high resolution aerial magnetometry, radiometry and electromagnetics cover large parts, but not all of the area. Detailed ground geophysics have been carried out in areas with known mineralisations. The data have not been used in this assessment.

Geochemistry including soil and stream sediment data, cover large parts, but not all of the area. Therefore, the data have not been used in this assessment.

Modelling by the MAP Wizard

For the input, the descriptive model is VMS (see section 3) and the subclass for the grade-tonnage model is VMS Mafic (see section 4.3 and data set in the appendix).

Grade-Tonnage model

1. Grade summary

Summary comparison of the pdf (probability density functions) representing the grades and the actual grades in the grade and tonnage model for the mafic subclass of VMS deposits.

Pdf type: normal
Pdf is not truncated.
Number of discovered deposits in the grade and tonnage model: 26
Number of resources: 2

Quantiles (reported in percent)
Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

	Component Cu		Component Zn		Component gangue	
	Gatm	Pdf	Gatm	Pdf	Gatm	Pdf
Minimum	0.5	0.0854	0.01	0.00248	85.0	20.1
0.25 quantile	1.0	1.0000	0.58	0.43500	96.9	95.6
Median	1.5	1.4700	1.10	0.99300	97.5	97.2
0.75 quantile	1.9	2.1500	2.00	2.25000	98.1	98.2
Maximum	10.0	19.4000	7.00	79.40000	98.6	99.8

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Compositional mean (reported in percent).		
	Gatm	Pdf
Cu	1.480	1.480
Zn	0.996	0.996
gangue	97.500	97.500

Composite variation matrix			
	Cu	Zn	gangue
Cu	0.000	1.56	0.334
Zn	1.560	0.00	1.520
gangue	0.334	1.53	0.000

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.
The composite variation matrix has two parts: its upper triangle and its lower triangle. The upper triangle is the upper triangle of the variation matrix for the actual grades in the grade and tonnage model. The lower triangle is the lower triangle of the variation matrix for the pdf that the represents the grades. Thus, corresponding elements in the upper and lower triangles should be compared to one another.

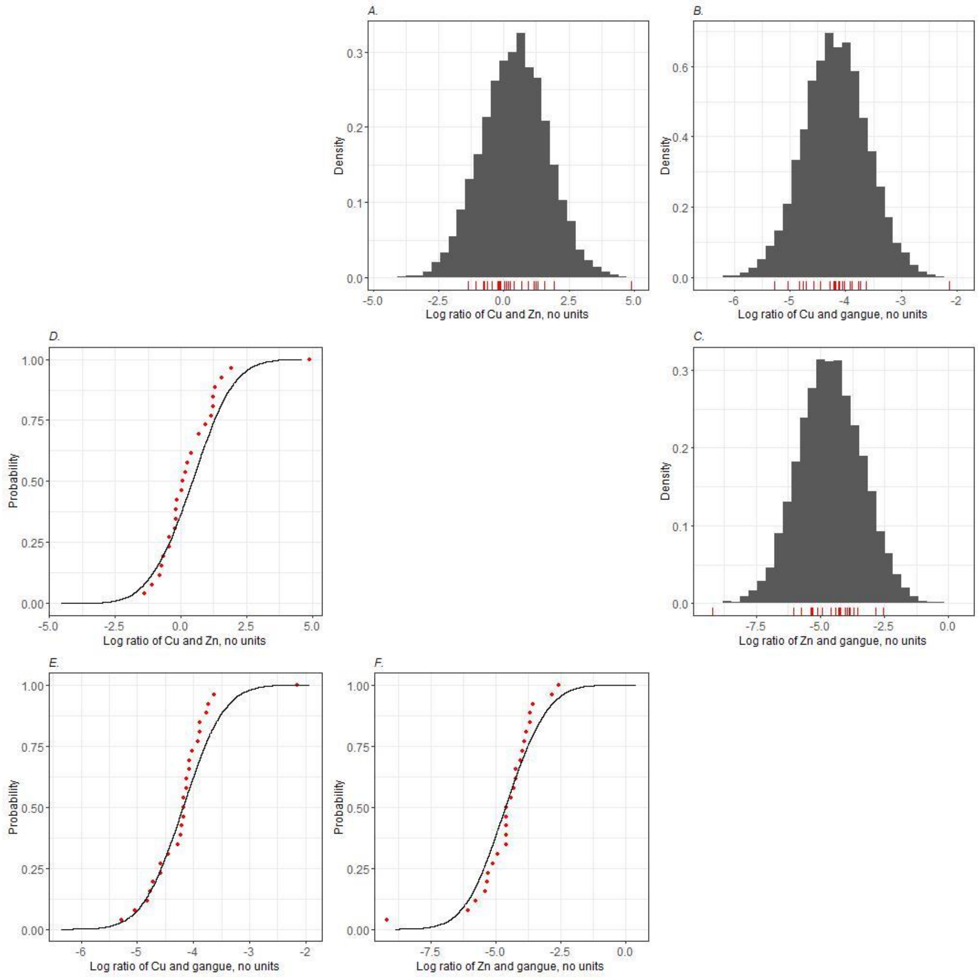

Figure 26: Histograms and cumulative distribution functions, calculated from the probability density function representing the grades. In A-C, vertical red lines (bottom) represent the log-ratios calculated from the grade-tonnage model. in D-F, the red dots are empirical distribution functions for the log-ratios calculated from the grade-tonnage model.

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2. Tonnage summary

Summary comparison of the pdf representing the tonnage and the actual tonnages in the model for VMS deposits of the mafic subclass.

Pdf type: normal

Pdf is not truncated.

Number of discovered deposits in the model: 26

Deviance = -19.8953

The left table pertains to the log-transformed tonnages. Column Gatm refers to the actual tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

The right table pertains to the (untransformed) tonnages. Column Gatm refers to the tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

	Gatm	Pdf
Minimum	11.70	7.15
0.25 quantile	13.50	13.30
Median	14.20	14.30
0.75 quantile	14.90	15.30
Maximum	17.20	21.10
Mean	14.30	14.30
St. deviation	1.46	1.46

	Gatm	Pdf
Minimum	120 000	12 700
0.25 quantile	700 000	594 000
Median	1 470 000	1 590 000
0.75 quantile	3 100 000	4 260 000
Maximum	30 000 000	1 420 000 000
Mean	4 520 000	4 610 000
St. deviation	7 540 000	12 400 000

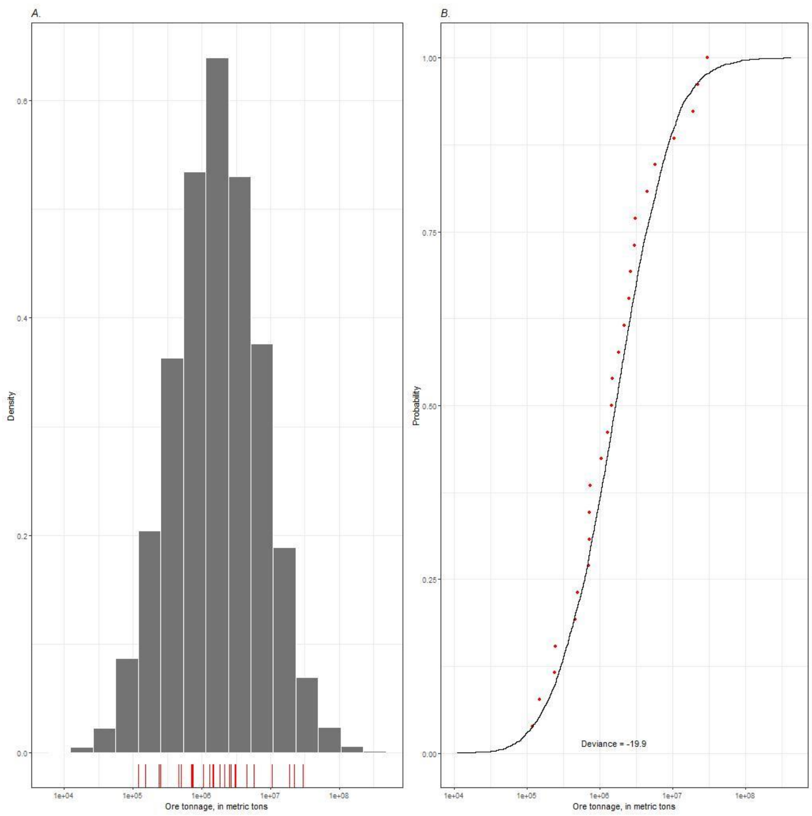

Figure 27: A) Probability density function that represents the ore tonnage in an undiscovered deposit. Vertical lines at the bottom represent the ore tonnages from the grade-tonnage model. B) Corresponding cumulative distribution function (solid line). The red dots are the empirical cumulative distribution function for the ore tonnages from the grade-tonnage model.

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Tract delineation

The Joma tract is delineated by the Røyrvik Group within the Orklump Nappe, and the corresponding units in Sweden. Because no other data than geology is covering the entire tract, the Tract Delineation Tool in MAP Wizard has not been used for the Joma tract.

Undiscovered deposits

1. Deposit density model

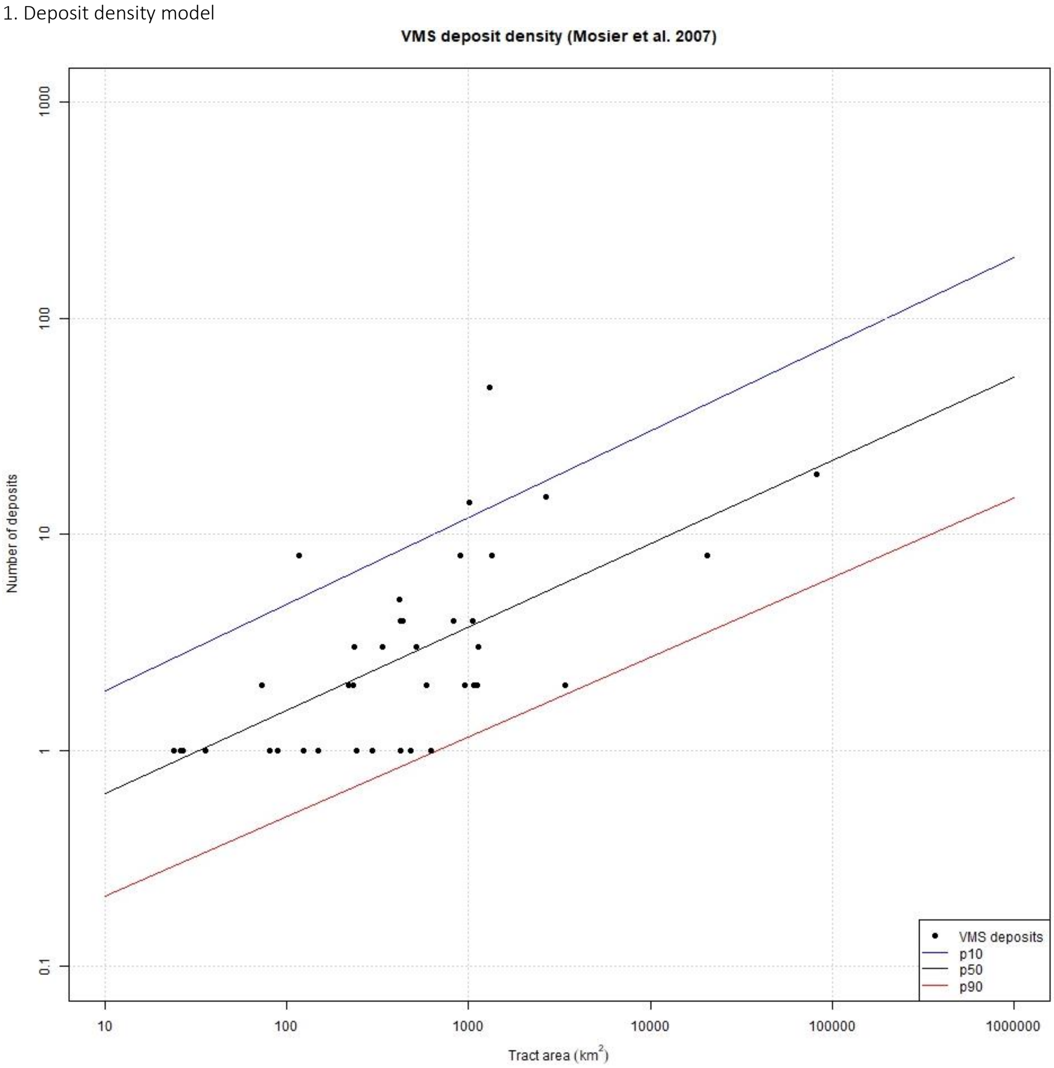

Figure 28: Plot of the VMS deposit density by Mosier et al. (2007).

The Joma tract is 290 km^2, which based on VMS deposit density model by Mosier et al. (2007) gives N90: 1, N50: 1, N10: 4.

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2. Negative binomial function and expert data

Expert	N90	N50	N10
MS	1	2	6
TB	1	2	6
OO	0	1	2
TG	0	1	3
KSA	1	2	6
AH	1	3	4
HS	0	1	4
BK	1	2	4
MST	1	2	4
STB	0	2	4
KSU	1	2	4
JSS	1	2	4
KR	0	1	5

Summary of pmf, number of undiscovered deposits	
Type	NegBinomial
Mean	2.31991
Variance	2.3015
St. Dev.	1.51707
Mode	2
Smallest N deposits in pmf	0
Largest N deposits in pmf	8
Inform. entropy	1.78653

Expert estimates of deposits in the Joma tract at 0.90, 0.50 and 0.10 probability and the resulting summary statistics for the probability mass function using the negative binomial option.

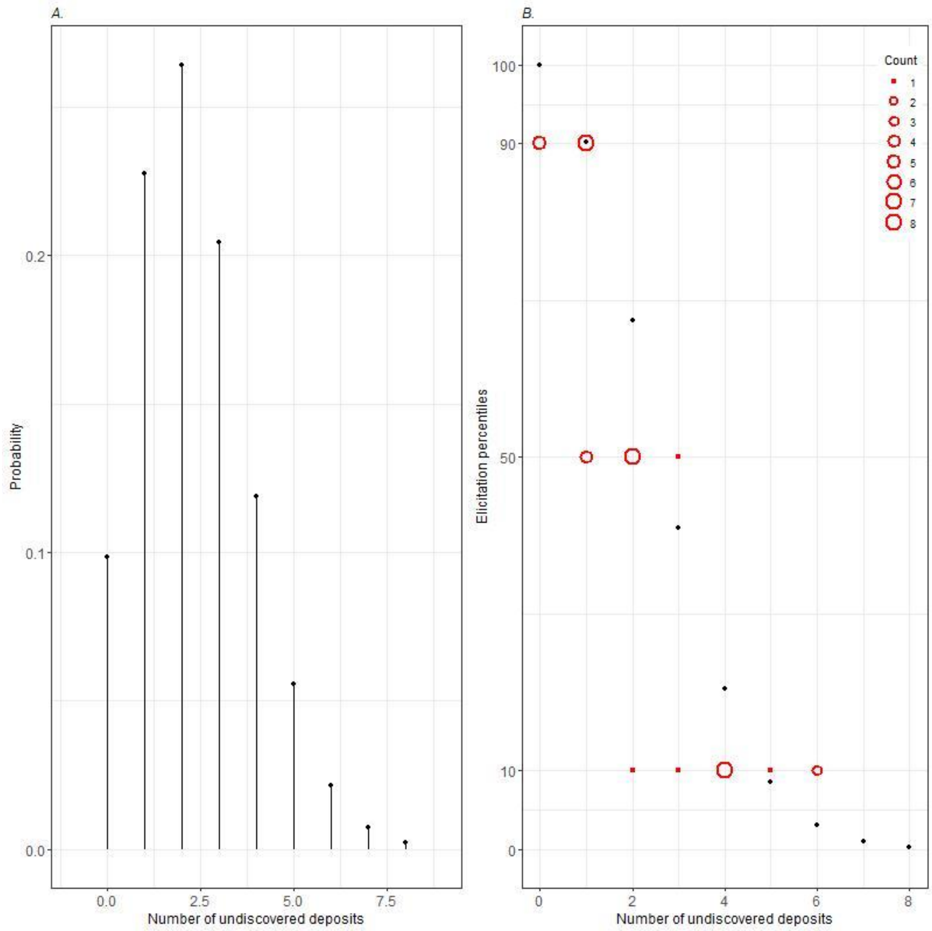

Figure 29 (left): Plot of the estimated probability mass function (pmf) using the negative binomial option. (Right): The corresponding cumulative distribution function with the expert estimates (red circles).

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Monte Carlo Simulation with Caledonian VMS Mafic Grade-Tonnage model

Summary of the pdf for the total ore and resource tonnages in all undiscovered deposits within the permissive tract.

Ore, Cu, Zn (Mt):

	0.05q	0.1q	0.25q	0.5q	0.75q	0.9q	0.95q	Mean	P (0)	P(>mean)
Ore	0	0.0235	1.400	4.960	12.50	25.80	38.70	10.60	0.0997	0.292
Cu	0	0.0003	0.0201	0.074	0.201	0.433	0.678	0.180	0.0997	0.279
Zn	0	0.00004	0.0122	0.058	0.184	0.469	0.839	0.209	0.0997	0.224

Explanation
" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix			
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn
Ore	10.6	10.7	Ore	18.8	20.1	Ore	NA	0.881	0.572
Cu	0.180	0.184	Cu	0.368	0.400	Cu	0.859	NA	0.520
Zn	0.209	0.212	Zn	0.589	0.733	Zn	0.557	0.510	NA

Explanation
1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.
2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

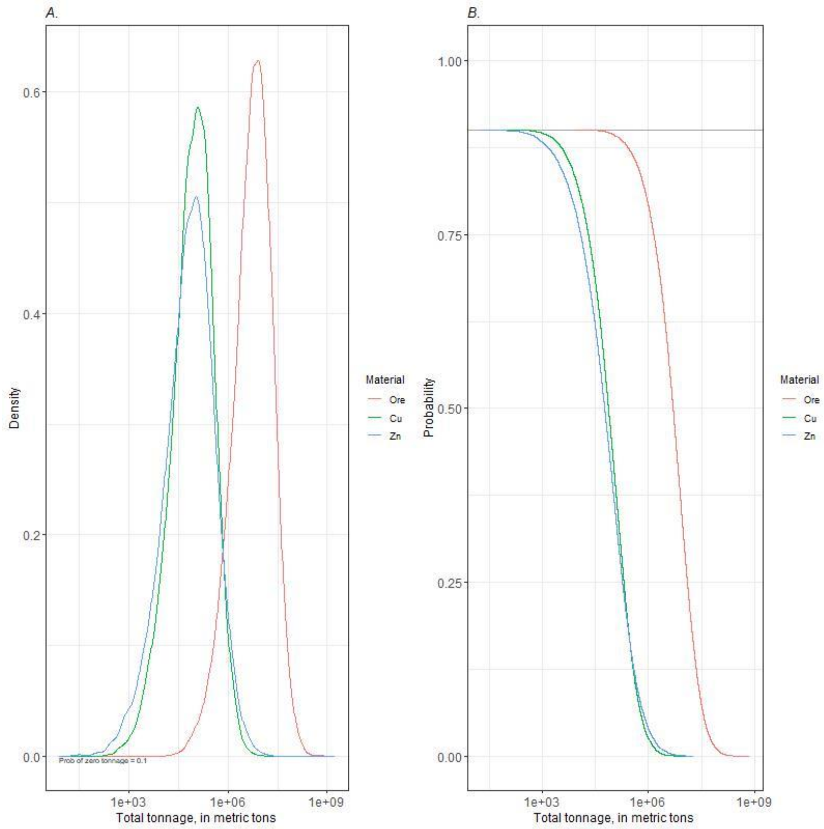

Figure 30: Plots of A) univariate marginal probability density functions and B) cumulative distribution functions for total ore Cu and Zn tonnages in the undiscovered deposits.

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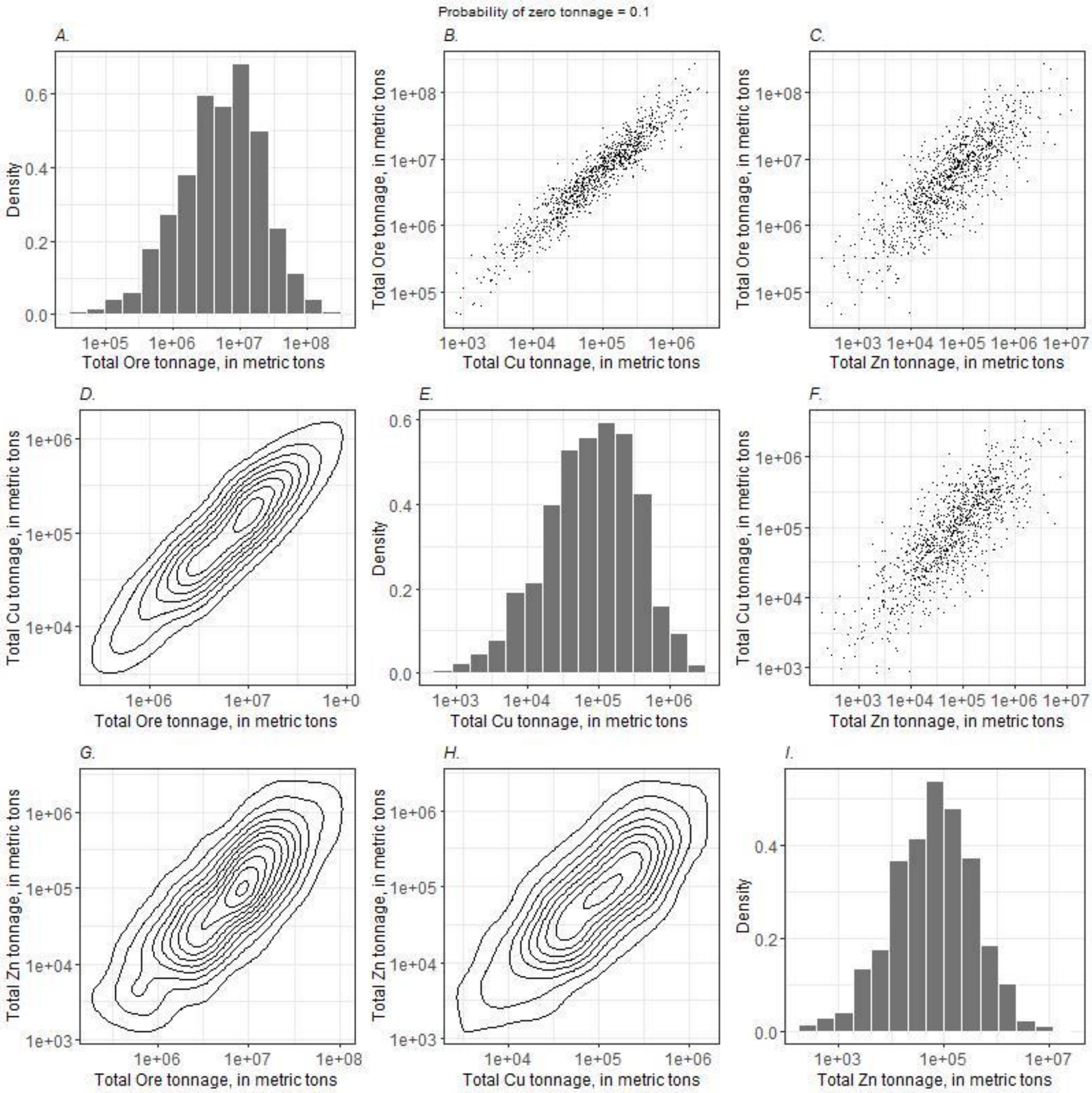

Figure 31: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

Economic Filter

The Economic filter tool estimates the proportion of the total estimated undiscovered resource that can be considered to be economically viable for mining. The tool applies simple engineering cost models to estimate the economic resource, and it is based on the USGS RAEF code (Shapiro & Robinson 2019).

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The Economic filter tool RAEF process allows the same run options as the USGS RAEF software: a) Batch run using preset parameter file, b) interactive run using GUI input of parameters and c) empirical mode run.

Input data for the filtering using interactive run (ref. Shapiro & Robinson 2019):

Tract area: Joma Tract 290 km^2
Simulated Deposits file: Monte Carlo Simulation Joma
Depth Intervals: 1; 0 - 1000 m and fraction 1
Deposit Type: Ore body massive/disseminated
Mine method: based on depth to the top of the deposit, if depth >= 61m: Block Caving, if depth < 61m: Open Pit
Mill type: 1 – Product flotation
Days of operation: 350 days
Marshall-Swift Cost updating index (MSC): 1.26
Investment rate of return: 0.15 (15 %)
Cap cost inflation factor: 1
Operating cost inflation factor: 1
CV_Cu, MRR_Cu: 3813.958, 0.91 (Commodity Value in 2008$/t, Metallurgical Recovery rate 91 %)
CV_Zn, MRR_Zn: 1851.864, 0.9 (Commodity Value in 2008$/t, Metallurgical Recovery rate 90 %)
Waste management options not chosen

Results:

Table 8: Summary statistics for in-ground contained resources and recovered resources (in Mt):

	means	min-max	median	std	P90	P70	P30	P10	Prob>=mean
Ore	10.6	0-730	5.0	19.0	0.0235	1.9721	10.289	25.76	0.2925
Cu_con	0.180	0-18	0.074	0.368	0.00279	0.0285	0.165	0.433	0.2788
Zn con	0.209	0-19	0.057	0.589	0.00004	0.0184	0.145	0.469	0.2245
Cu rec	0.131	0-16	0.035	0.315	0	0	0.109	0.341	0.26525
Zn rec	0.163	0-16	0.028	0.502	0	0	0.103	0.381	0.21985
NPV_tr	1.8e08	0-9.1e09	2.7e07	4.4e08	0	0	1.2e08	4.8e08	0.24065

NPV_area: 605121

Table 8 shows statistics for the deposit ore tonnage in million metric tons (Mt), contained in-ground mineral resource tonnage (Cu_con, Zn_Con, in Mt), recovered mineral resource tonnage (Cu_rec, Zn_rec, in Mt) and net present value of the tract (NPV_tr) in 2008$. The net present value pr km^2 is shown below the table; 605121 $(2008)/km^2.

Table 9: Estimates of mean contained and recovered resources by commodity for the user-defined depth intervals (in Mt):

Depth interval	Cu_con_means	Cu_rec_means	Zn_con_means	Zn_rec_means	ProbOfZero
0-1000 m	0.180	0.131	0.209	0.163	0.5782

For the chosen depth interval 0-1000 m, Table 9 lists the mean statistics for the contained and recovered resources of Cu and Zn in million tons in the Joma tract.

The Economic Filter generates two graphs that show estimated ore deposit cutoff grade and recovered ore value as a function of ore tonnage, mine type, and deposit depth. In Figure 32, cutoff grade is expressed as copper equivalent grade (CuEQ%); in Figure 33, cutoff grade is expressed as ore value (in dollars per ton) based on the metallurgical recovery.

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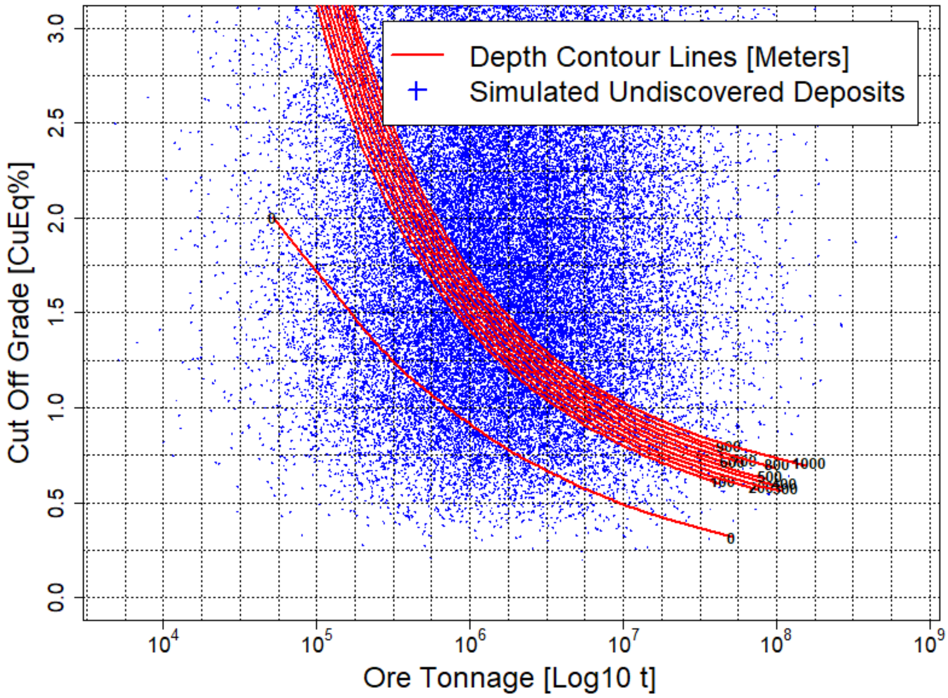

Figure 32: Copper equivalent (CuEQ%) grade/tonnage plot with cutoff grade versus deposit tonnage as a function of depth to top of the deposit in meters.

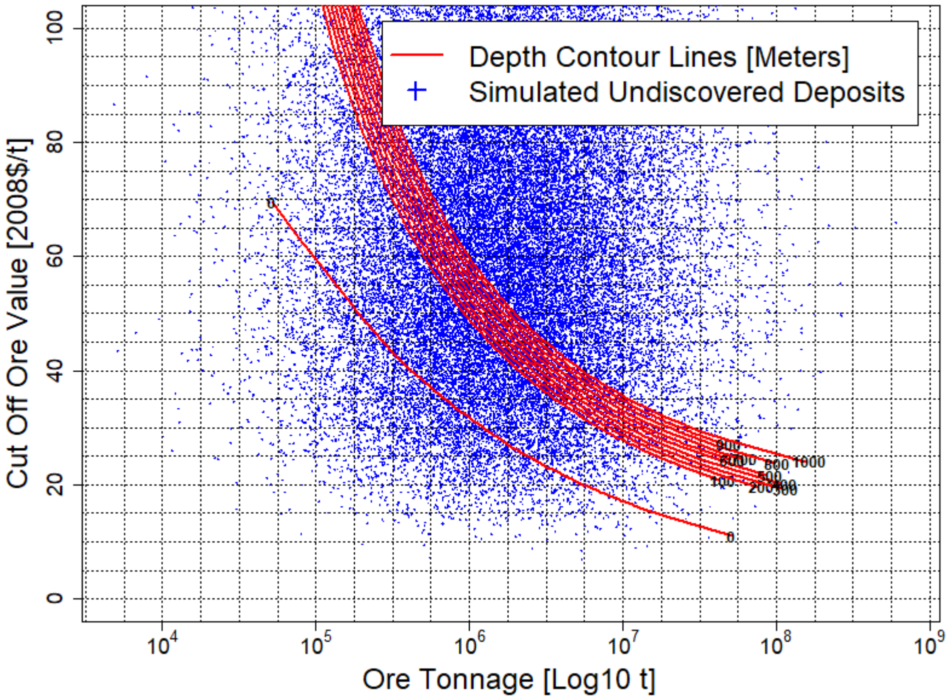

Figure 33: Ore value/tonnage plot with cutoff ore value versus deposit tonnage as a function of depth to top of the deposit in meters.

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Summary of the modelling for the Joma Tract

Descriptive Model: VMS

Grade-Tonnage Model for Mafic VMS class: Mean (pdf): 1.48 % Cu, 1.00 % Zn, 4.61 Mt; Median (pdf): 1.47 % Cu, 0.99 % Zn, 1.59 Mt

Tract Delineation: The Røyrvik volcanosedimentary group within the Orklump Nappe and corresponding units in Sweden, area 290 km^2

Undiscovered deposits: VMS deposit density model gives 1 deposit @ N90, 1 deposit @ N50, 4 deposits @ N10. Expert data and negative binomial function: mean number of undiscovered deposits are 2.3

Monte Carlo Simulation – ore and resource tonnages in the undiscovered deposits: (mean) 10.6 Mt ore, 0.180 Mt Cu, 0.209 Mt Zn, (median) 4.96 Mt ore, 0.074 Mt Cu, 0.058 Mt Zn

Economic Filter (commodity value in 2008$/ton): mean value of tract 180 mill. $ (median 27 mill $), mean contained Cu 180 000 t and recovered Cu 131 000 t, mean contained Zn 209 000 t and recovered Zn 163 000 t.

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4.6. Assessment for the Stekenjokk Tract

Description of the tract

The Stekenjokk area is located in mountainous terrain (the Caledonides) in the westernmost part of County of Västerbotten, close to the border to Jämtland County and to Norway (Figure 34).

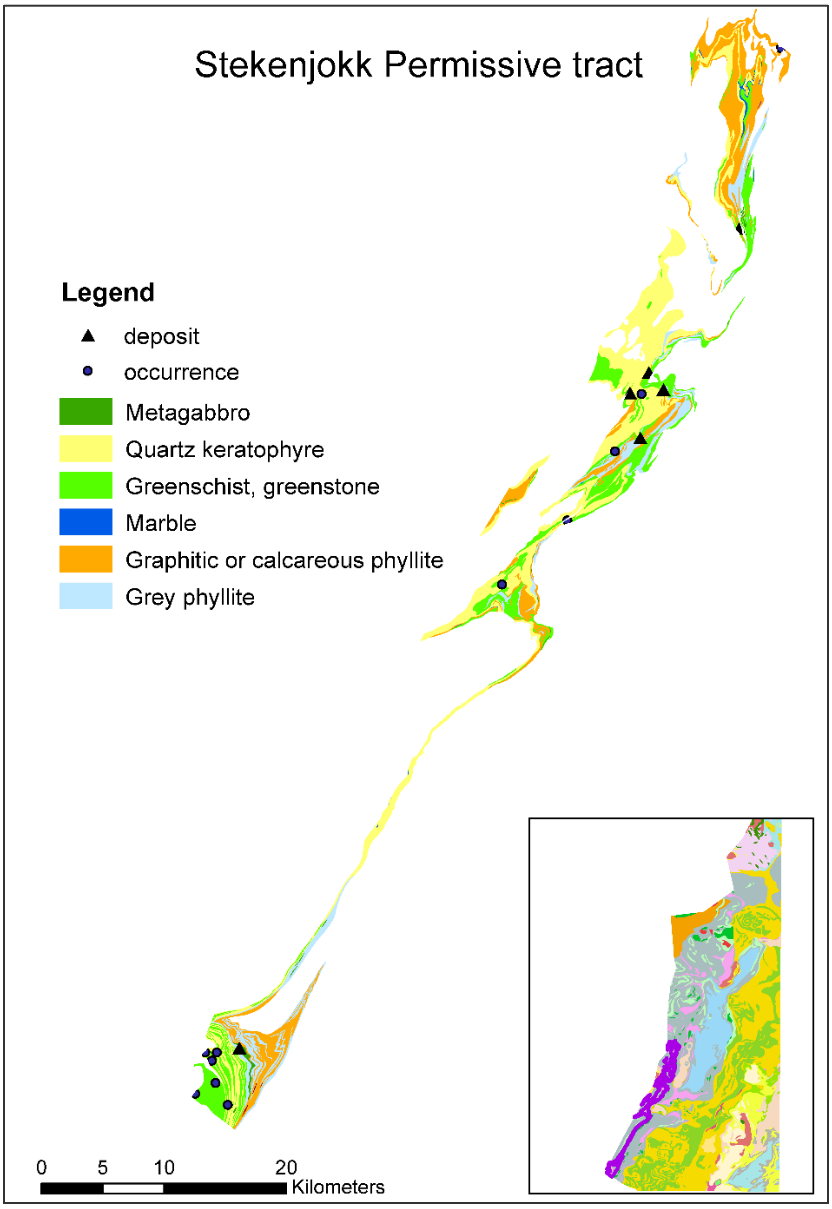

Figure 34: Geology of the Stekenjokk tract, based on SGU bedrock database. Known mineralisations (from SGU ore database) are also shown.

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The Stekenjokk quartz keratophyre (Zachrisson 1964) is a c. 650 m thick sequence of quartz keratophyre (altered dacite) interlayered with green tuffite in the upper part and intruded by quartz keratophyre and basic intrusions in the lower part. There are two geochemical suites: an older with an island-arc tholeiite signature and a younger, largely intrusive, with ocean-floor basalt signature (Stephens 1980, 1982). Age determinations have given ages of 492 Ma and 476 Ma (Claesson et al. 1988). The Stekenjokk-Levi massive sulphide deposit (Zachrisson 1986a, b) occurs as a stratiform layer in the stratigraphically uppermost part of the Stekenjokk quartz keratophyre. A graphitic phyllite that overlies the ore has unusually high concentrations of uranium, vanadium and molybdenum and has, based on this, been correlated with the Cambrian-Ordovician alum shales in the platformal sedimentary cover (Sundblad & Gee 1984). However, such enriched shales also occur in Gander in the Appalachian and in Wales, so there are likely several independent deposits (M.B. Stephens pers. com. Dec-2019).

The Lasterfjället greenschist (Zachrisson 1964) is dominated by greenschist, with subordinate phenocryst-bearing greenstone and phyllite. The geochemical composition resembles ocean-floor basalt (Stephens 1980, Stephens et al. 1985).

Deposits and prospects in the Stekenjokk tract

There are three known deposits within the Stekenjokk tract (Table 10), of which one of them has been mined in the past between 1976-1988 (Stekenjokk).

Table 10: Deposit data for the Stekenjokk tract

Name	east	north	Total tonnage	Host	Grade (%)	Reference
Tjokkola	471995	7219503	0.17 Mt	tuffite, quartz keratophyre	0.89 Cu, 2.20 Zn	Sandstad & Hallberg 2012, MiS 2 p. 56-58; mink99001; brap81566; brap00039; SGU_ai_74
Levimalmen (Levi)	473538	7221168	5.10 Mt	quartz keratophyre	1.20 Cu, 1.80 Zn	Sandstad & Hallberg 2012, mink99001; brap81505; brap00071; prap84532; brap81566; SGU_ai_74
Stekenjokk	474721	7219781	11.90 Mt	quartz keratophyre, tuffite, graphitic phyllite	1.30 Cu, 3.80 Zn	MetalProspecting AS (NI 43-101), SGU Ai 73-74; mink99001; mink96184; brap82541; brap81566; www.vilhelminamineral.se; SGU_ai_74

Mt – million metric tons

The *Stekenjokk* deposit is a volcanogenic strata-bound deposit hosted by felsic-dominated volcanic rocks. Stratigraphic footwall to the ore is sodic-altered felsic volcanic rocks, the Stekenjokk quartz keratophyre, that were altered during mineralization. The volcanic rocks, Ordivician in age, belong to the Stikke nappe which is part of the middle Köli nappes. The massive ore is capped by black phyllite rocks and post-ore volcanic rocks. Sulfide ore at Stekenjokk can be divided into massive (py+sph+cpy) and disseminated (po+cpy) ore, the former interpreted to be exhalative ore deposited on the seabed, the latter a stringer zone to the exhalative ore (Zachrisson 1984, 1986a). The ore and its host rock have been intensely deformed. Zachrisson (1971) showed that the nearby Levi orebody is part of the same mineralized system as the Stekenjokk ore. Stekenjokk together

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with the Levi deposit to the north make up a 9 kilometres long orebody where the contact between Stekenjokk and Levi has been eroded away at a length of 1.5 kilometres. The ore at Stekenjokk is folded in a very complicated way and examinations of the country rocks indicate that the stratigraphy is inverted.

The *Levi* deposit constitutes the stratigraphic continuation of the Stekenjokk ore to the north but is separated from Stekenjokk by the ore-bearing layer being eroded away. The style of mineralization and hostrocks are thus similar to Stekenjokk; a massive pyritic and a disseminated pyrrhotitic ore hosted by felsic volcanic rocks as the stratigraphic foot wall and graphitic phyllite intruded by gabbroic dikes as hanging wall. Mining never took place at Levi but several ore resource estimates have been made. The most recent report 5.14 Mt @ 1,25 % Cu, 1.84 % Zn and 24 g/t Ag and smaller amounts of lead.

The *Tjokkola* deposit located 2,7 kilometers west of the Stekenjokk deposit was found in 1959 by boulder tracking and ground geophysics followed by drilling. A resource estimated, non-compliant to CRIRSCO, indicate 169 000 ton @ 0.89 % Cu and 2.2 % Zn with low grades of lead, silver and gold. Ore at Tjokkola consist of two mineralized layers about 15-20 meters apart. They consist of disseminated chalcopyrite, sphalerite, pyrrhotite and pyrite hosted by chlorite-sericite schist interpreted to be hydrothermally altered felsic volcanic rocks.

In addition to the three deposits, there are 12 prospects and occurrences, which have been characterized as bimodal-felsic VMS in the Stekenjokk permissive tract. They are listed in Table 11.

Table 11: Deposit data for prospects in the Stekenjokk tract.

Name	east	north	Host rock	Cu (%)	Zn (%)	Pb (%)	Ag(g/t)	Au (g/t)
Björkvattnet	440092	7165925	tuffitic greenschist, graphitic tuffite	0.73	0.40	0.05	4	0.17
Beitsetjenjunje	480926	7232915	greenschist	0.97	1.00	0.16	13	0.19
Gelvenåkko	472825	7215801	greenschist, quartz keratophyre	1.84	1.63	0.42	16	0.1
Bustadmyren	439169	7161234	quartz keratophyre	0.40	2.42	0.09	7	
Hålbåcksgruvan	437851	7164869	greenschist	1.02	0.02			
Portfjället	436497	7162169	tuffitic greenschist	0.16	0.54	0.41	18	
Björkvattnet Sydvåstra	438173	7163034	tuffitic greenschist	0.01	0.02	0.01		
Björkvattnet Våstra	438262	7165530	greenschist	0.56	0.03			
Sarapmalmen	470804	7214677	tuffite	0.33	0.50			
Zinkbländemalmen	472974	7219384	quartz keratophyre	0.13	2.99	0.1	22	0.1
Malmforsen	461571	7203808	quartz keratophyre	0.22	0.36		6	
Raurotjuolta	466903	7209038	quartz keratophyre	0.03	13.19	0.97	82	

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Exploration data

Exploration in the Swedish Caledonides was initiated by the wish to find sulfide ores similar to those that were known in similar geological setting in Norway.

During geological reconnaissance work in 1918, ore boulders and a small outcrop of massive pyrite ore was found in the Stekenjokk area (Zachrisson 1971). Subsequent geological mapping, electric measurements, trenching and drilling in 1918-1925 in the Remdalen and Stekenjokk areas defined the Stekenjokk ore (Högbom 1925). Subsequent drilling in 1918-1921 and 1952-1963 led to the opening of the mine and dressing plant in 1976. Exploration work was also conducted in the Remdalen area north of Stekenjokk. Further exploration was done in 1952-1966 including drilling and geochemical investigations. During this campaign the Levi ore body was found. In 1963-1966 an underground survey was conducted by the Boliden Company, a work ordered by the Kommerskollegium (Bureau of Mines). Ore estimates made after the mine closed indicate resources of 4.96 Mt. (non-compliant to CRIRSCO). Ore production at Stekenjokk started in 1976 and lasted for 12 years. In 1988 the Stekenjokk mine and concentrator was closed. The mine closed in 1988 and had then produced 6,97 Mt of Cu-Zn-Ag-(Pb-Au) ore.

The airborne geophysical data (total magnetic field, VLF and gamma radiation) collected by routine SGU's measurements cover mainly very small parts of the selected areas in this part of the project. Moreover, the flight line spacing of 400 m affects the resolution of data considerably and as a result such data are not shown in this report. We have searched the SGU's digital database and compiled the exiting ground geophysical measurements. Most of the data are acquired in the 80's. The measured methods include ground magnetics and slingram. The magnetic field data are limited to considerably small areas which most probably has been acquired in conjunction with smaller exploration targets. The slingram data cover reasonably larger areas as shown in Figure 35b. The data acquisition parameters are summarized in Table 12.

Table 12: Acquisition parameters of the ground slingram measurements in the study area

Measured parameter	Frequency (Hz)	Measurement year	Coil Separation (m)
Real and imaginary in ppm	3500	1947-1974	20, 40, 80
Real and imaginary in ppm	18000	1965-1974	40, 60

In order to study correlation between the variation of apparent resistivity and different geological units shown in Figure 34, we have divided the area covered by the slingram into three smaller areas as shown in Figure 35a. For the Stekenjokk area and the area covered by the slingram are shown in Figure Figure 35b.

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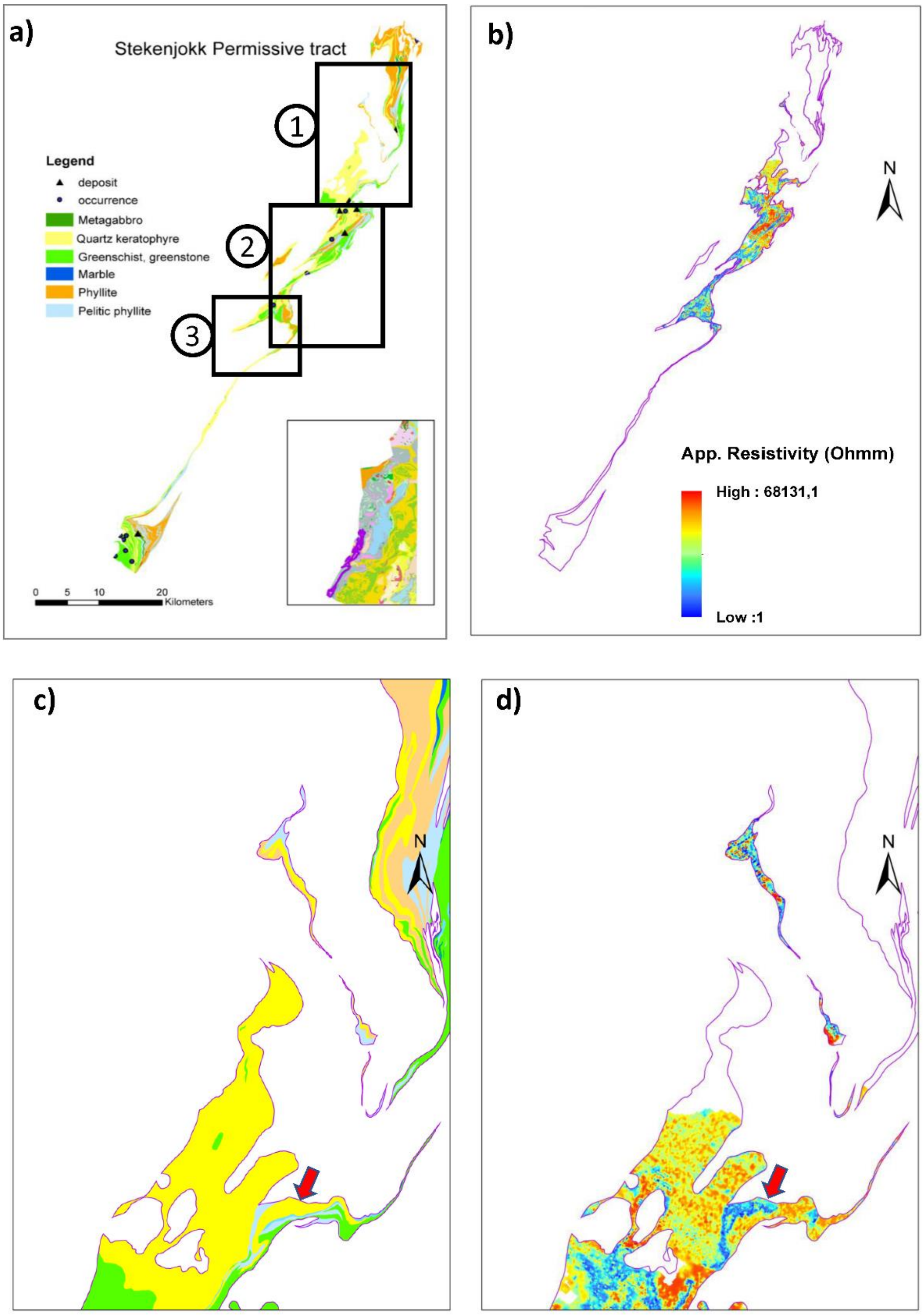

Figure 35: Location of smaller areas (1-3) for detailed demonstration of apparent resistivity data from the slingram measurements in the studied areas. a) location of subareas on the geological map, b) existing resistivity data in the Stekenjokk permissive tract, c) geological map of subarea 1 and d) resistivity map in subarea 1. Note that the magenta polylines in (a & d) mark boundaries of the area. The red arrows in (c) and (d) indicate correlation between the distinct low-resistivity zone and the mapped dacitic-rhyolitic rocks.

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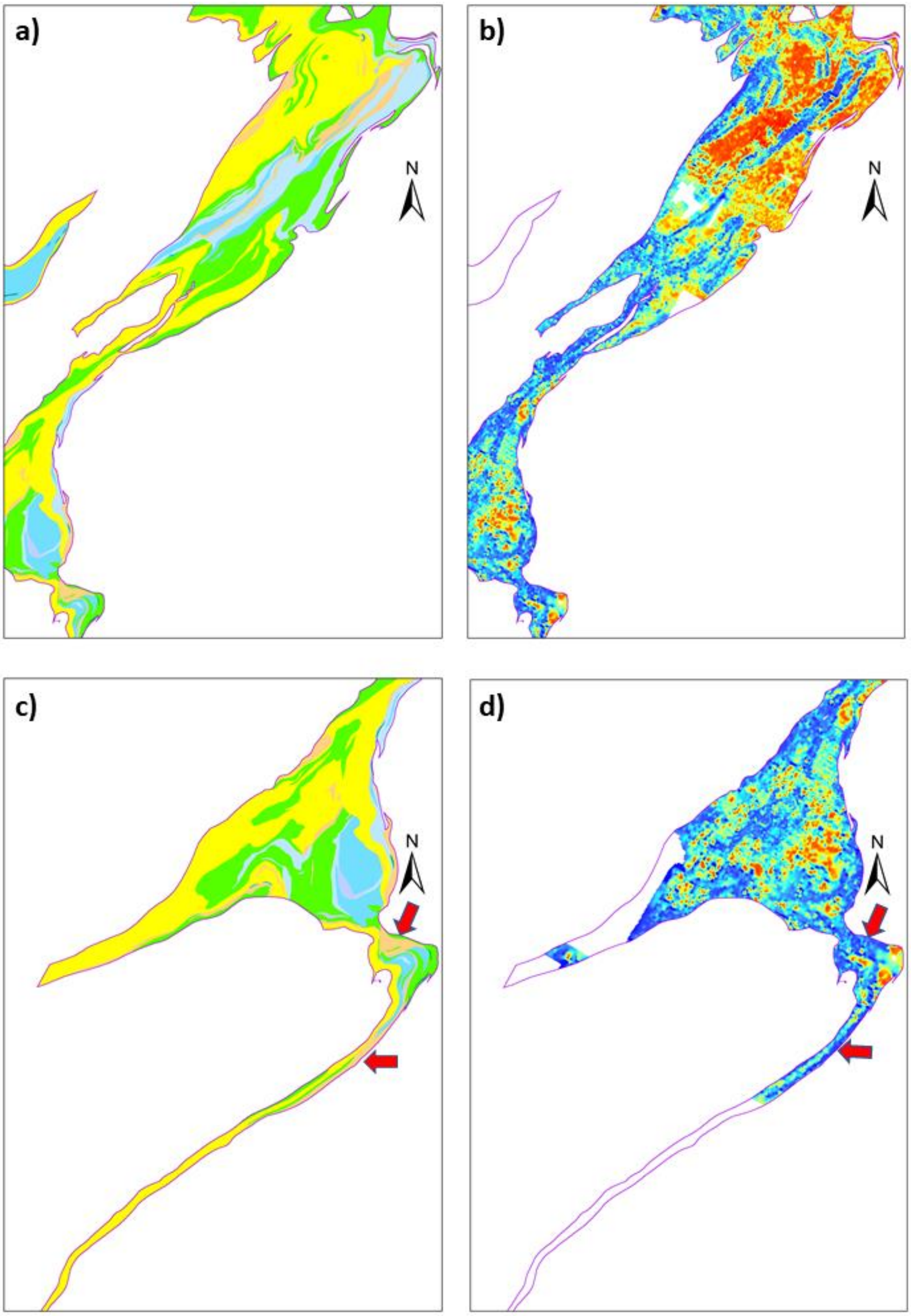

Figure 36: Comparison between the underlying geology (a & c) and the existing apparent resistivity data (b&d) in Subareas 2 and 3. For the location of subareas see Figure 35 a. The red arrows in (c) and (d) indicate correlation between the distinct low-resistivity zones and the mapped phyllites.

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In subarea 1 (Figure 35 c, d) there is a general correlation trend between the medium to low-resistivity zones and the mapped dacitic-rhyolitic volcanic rocks which are associated with sulphide mineralization in the area. One very distinct low-resistivity zone in subarea 1 is marked by a red arrow in Figure 35c and Figure 35d. The basaltic-andesitic rocks appear generally as high resistivity zones. In subarea 2 (see Figure 35 a for the location) the bedrock map reveals a more complicated geology (Figure 36a) which is also observed in the map of resistivity showing a more complicated variation pattern (Figure 36b). In the north-eastern parts of subarea 2 there are two distinct elongated NE-striking low-resistivity zones that nearly follow the mapped phyllites. The high-resistivity zones, on the other hand, match the areas mapped as basaltic-andesitic volcanic rocks. Further to south the mapped conglomerates correlate very well with the high-resistivity zones. In subarea 3, there are two distinct low-resistivity anomalies marked by the red arrows (Figure 36d) that are clearly correlated with the presence of phyllites shown on the bedrock geology map in Figure 36c. Similar to the other two subareas the dacitic-rhyolitic areas have generally a strong correlation with low to medium-resistivity zones.

Modelling by the MAP Wizard

For the descriptive model, the VMS model was used (see section 3) and for the grade-tonnage model, data for the VMS bimodal-felsic subtype was used (see section 4.3 and data set in the appendix).

Grade-Tonnage model

1. Grade summary
Summary comparison of the pdf (probability density functions) representing the grades and the actual grades in the grade and tonnage model for the bimodal-felsic subclass of VMS deposits.

Pdf type: normal
Pdf is not truncated.
Number of discovered deposits in the grade and tonnage model: 55
Number of resources: 2

Quantiles (reported in percent)
Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

	Component Cu		Component Zn		Component gangue	
	Gatm	Pdf	Gatm	Pdf	Gatm	Pdf
Minimum	0.100	0.00801	0.07	0.00849	81.9	8.38
0.25 quantile	0.355	0.38300	1.89	1.34000	93.0	92.40
Median	0.730	0.66300	4.30	2.98000	95.0	96.0
0.75 quantile	1.300	1.14000	6.24	6.53000	97.0	97.8
Maximum	2.480	26.10000	17.00	91.50000	99.7	99.90

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Compositional mean (reported in percent).		
	Gatm	Pdf
Cu	0.681	0.681
Zn	2.990	2.990
gangue	96.300	96.300

Composite variation matrix			
	Cu	Zn	gangue
Cu	0.000	2.08	0.662
Zn	2.090	0.00	1.480
gangue	0.662	1.48	0.000

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.
The composite variation matrix has two parts: its upper triangle and its lower triangle. The upper triangle is the upper triangle of the variation matrix for the actual grades in the grade and tonnage model. The lower triangle is the lower triangle of the variation matrix for the pdf that the represents the grades. Thus, corresponding elements in the upper and lower triangles should be compared to one another.

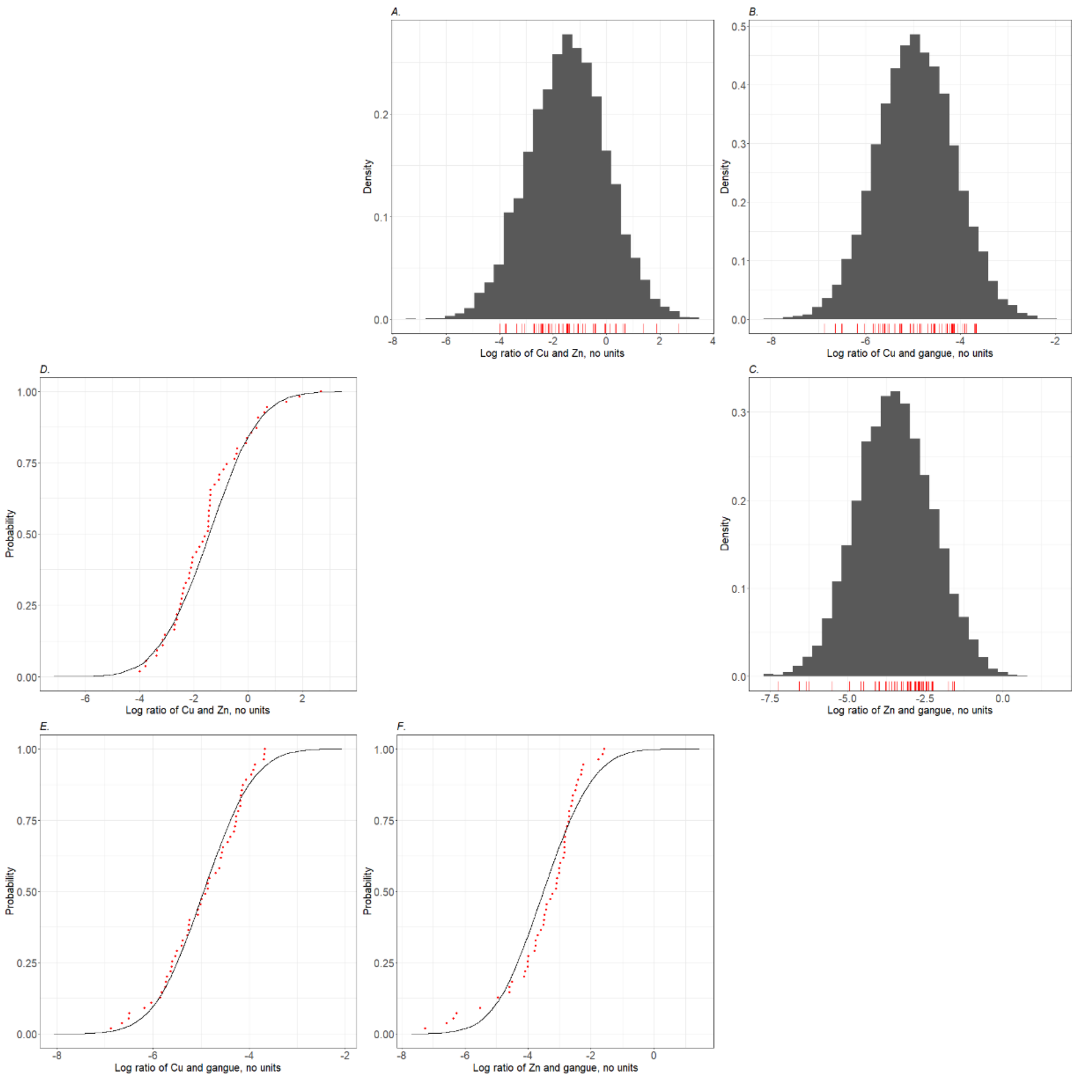

Figure 37: Histograms and cumulative distribution functions, calculated from the probability density function representing the grades. In A-C, vertical red lines (bottom) represent the log-ratios calculated from the grade-tonnage model. in D-F, the red dots are empirical distribution functions for the log-ratios calculated from the grade-tonnage model.

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2. Tonnage summary

Summary comparison of the pdf representing the tonnage and the actual tonnages in the model for VMS deposits of the bimodal-Felsic subclass.

Pdf type: normal

Pdf is not truncated.

Number of discovered deposits in the model: 55

Deviance = -17.2626

The left table pertains to the log-transformed tonnages. Column Gatm refers to the actual tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

The right table pertains to the (untransformed) tonnages. Column Gatm refers to the tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

	Gatm	Pdf
Minimum	10.8	5.41
0.25 quantile	12.9	13.00
Median	14.2	14.20
0.75 quantile	15.30	15.40
Maximum	18.7	22.50
Mean	14.2	14.20
St. deviation	1.8	1.80

	Gatm	Pdf
Minimum	50 000	224
0.25 quantile	410000	430000
Median	1400000	1440000
0.75 quantile	4450000	4850000
Maximum	137000000	6130000000
Mean	7470000	7220000
St. deviation	21000000	33700000

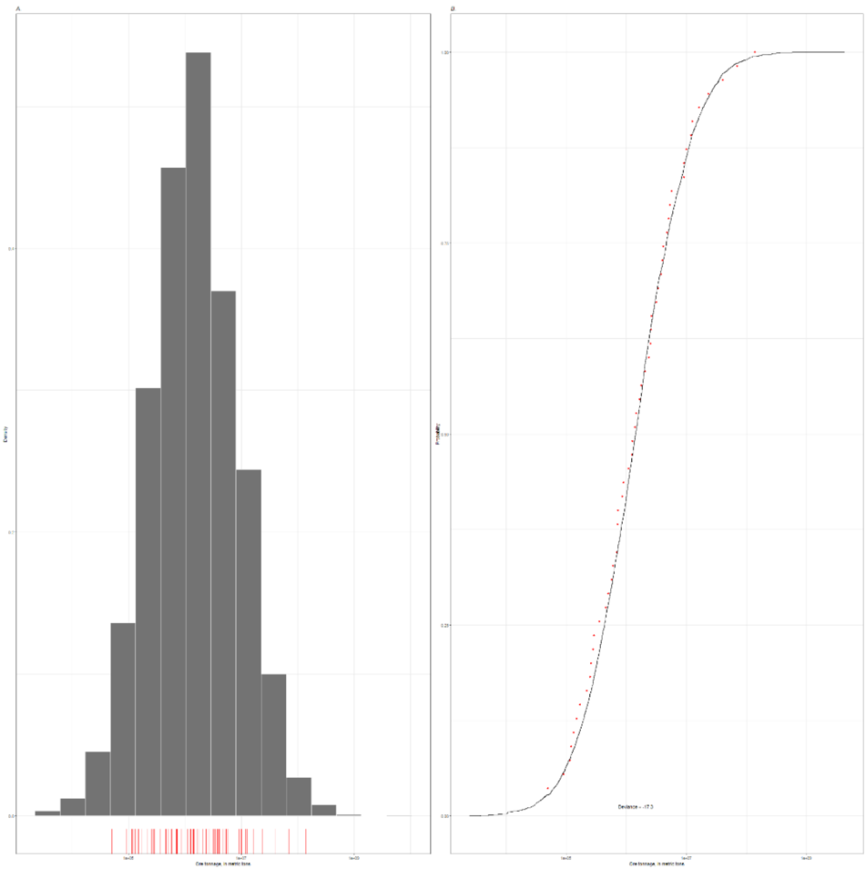

Figure 38: A) Probability density function that represents the ore tonnage in an undiscovered deposit. Vertical lines at the bottom represent the ore tonnages from the grade-tonnage model. B) Corresponding cumulative distribution function (solid line). The red dots are the empirical cumulative distribution function for the ore tonnages from the grade-tonnage model.

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Tract delineation

The Stekenjokk tract is restricted by the Stekenjokk Quartz-Keratophyre unit in the Stikke Nappe. Because there are limited other data than geology covering the tract, the Tract Delineation Tool in MAP Wizard has not been used for the Stekenjokk tract.

Undiscovered deposits

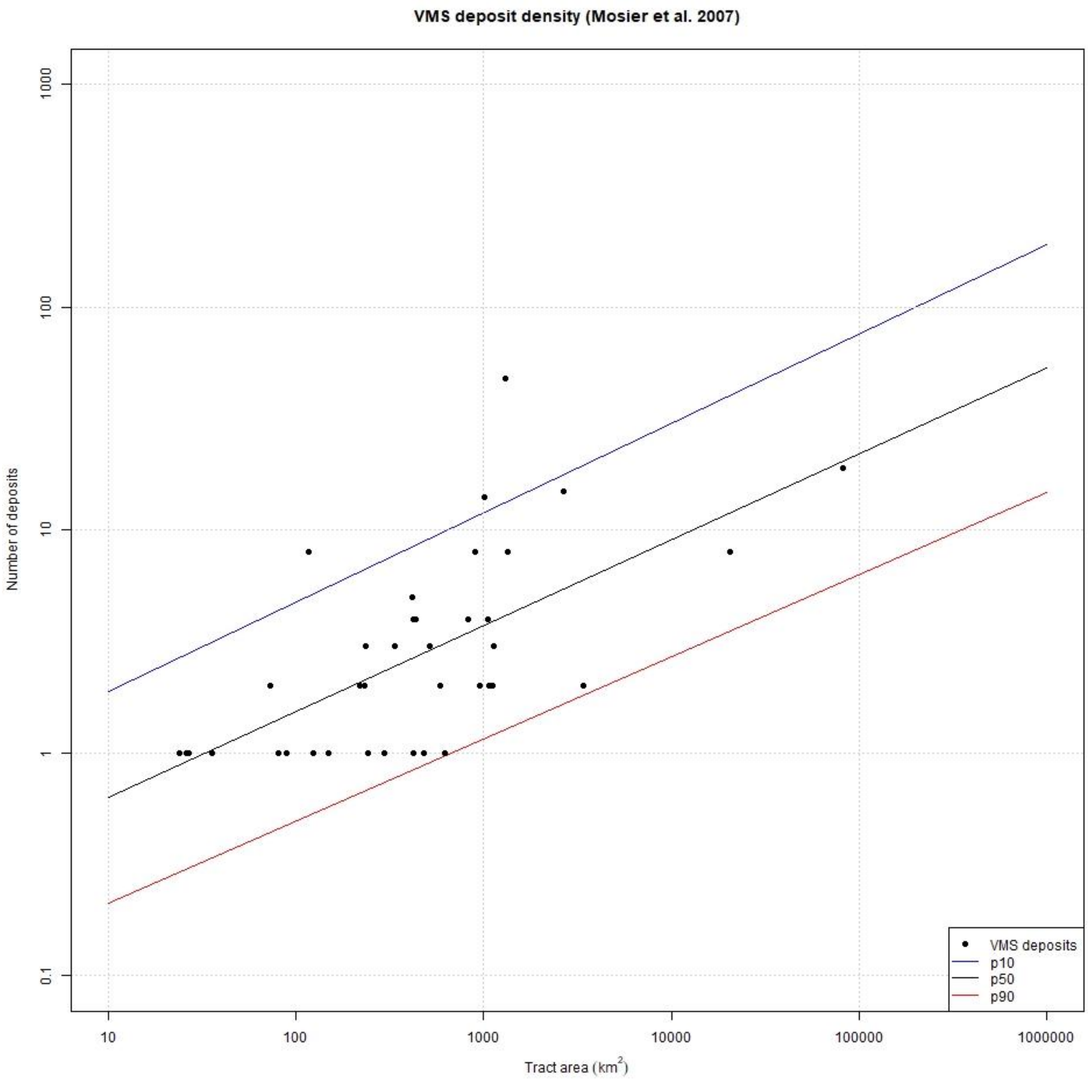

Figure 39: Plot of the VMS deposit density by Mosier et al. (2007).

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2. Negative binomial function and expert data

Expert	N90	N50	N10
KR	2	3	8
HS	0	2	4
AH	2	5	12
KSA	0	1	4
BK	0	2	4
MS	1	3	5
JSS	1	2	4
TB	1	2	5
TG	1	3	5
MST	1	2	4
SB	1	2	3

Summary of pmf, number of undiscovered deposits	
Type	NegBinomial
Mean	2.46455
Variance	2.46124
St. Dev.	1.56884
Mode	2
Smallest N deposits in pmf	0
Largest N deposits in pmf	9
Inform. entropy	1.82262

Expert estimates of deposits in the Stekenjokk tract at 0.90, 0.50 and 0.10 probability and the resulting summary statistics for the probability mass function using the negative binomial option.

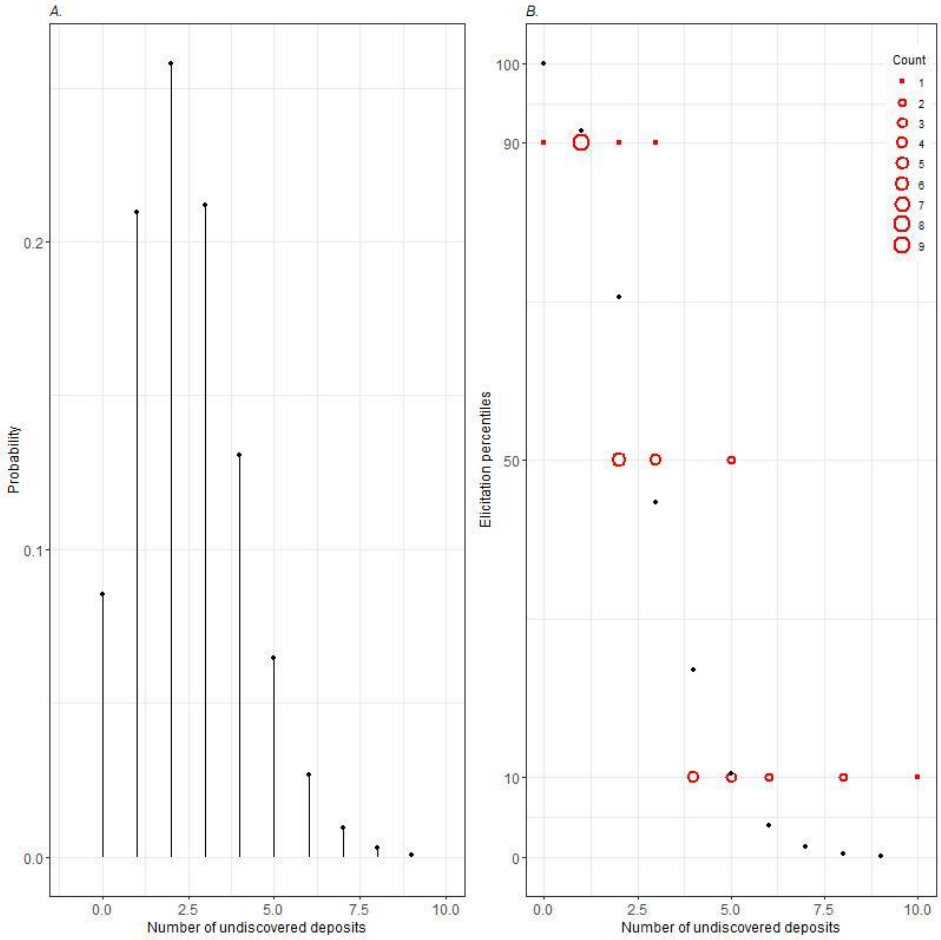

Figure 40 (left): Plot of the estimated probability mass function (pmf) using the negative binomial option. (Right): The corresponding cumulative distribution function with the expert estimates (red circles).

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Monte Carlo Simulation with Caledonian VMS Bimodal-Felsic Grade-Tonnage model

Summary of the pdf for the total ore and resource tonnages in all undiscovered deposits within the permissive tract.

Ore, Cu, Zn (in Mt):

	0.05q	0.1q	0.25q	0.5q	0.75q	0.9q	0.95q	Mean	P (0)	P(>mean)
Ore	0	0.0907	1.430	5.720	17.00	40.50	68.00	17.70	0.0863	0.241
Cu	0	0.000421	0.00895	0.0409	0.133	0.350	0.618	0.158	0.0863	0.218
Zn	0	0.00156	0.0382	0.1960	0.690	1.980	3.720	0.949	0.0863	0.198

Explanation

" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix			
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn
Ore	17.70	17.80	Ore	49.80	54.00	Ore	NA	0.810	0.648
Cu	0.158	0.162	Cu	0.564	0.655	Cu	0.733	NA	0.423
Zn	0.949	0.9520	Zn	3.660	4.740	Zn	0.642	0.419	NA

Explanation

1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.
2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

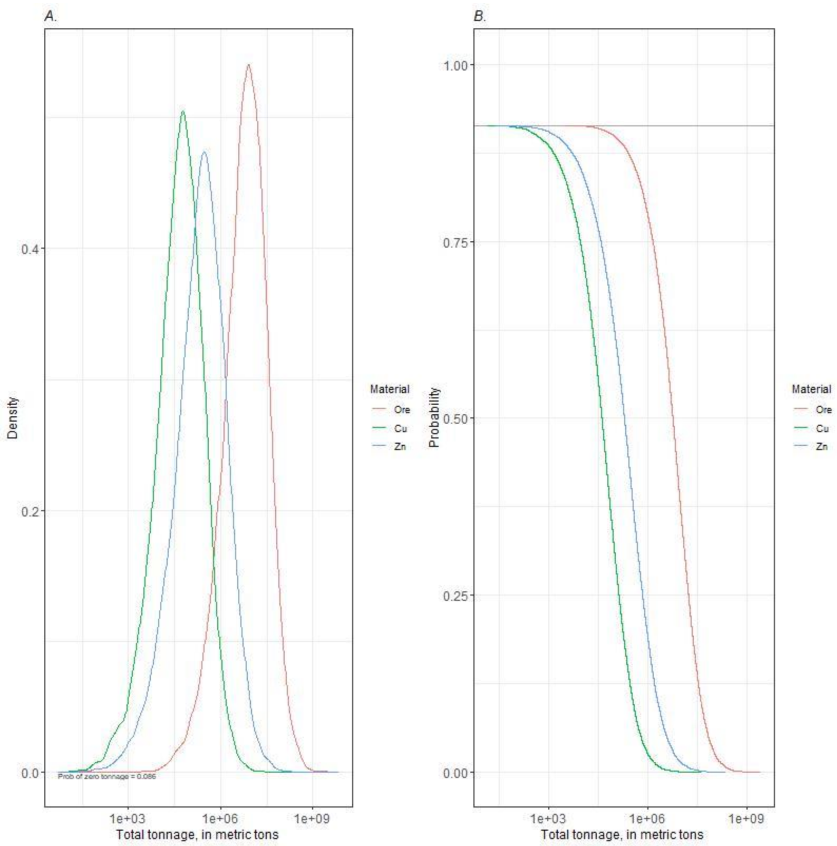

Figure 41: Plots of A: univariate marginal probability density functions and B: cumulative distribution functions for total ore Cu and Zn tonnages in the undiscovered deposits.

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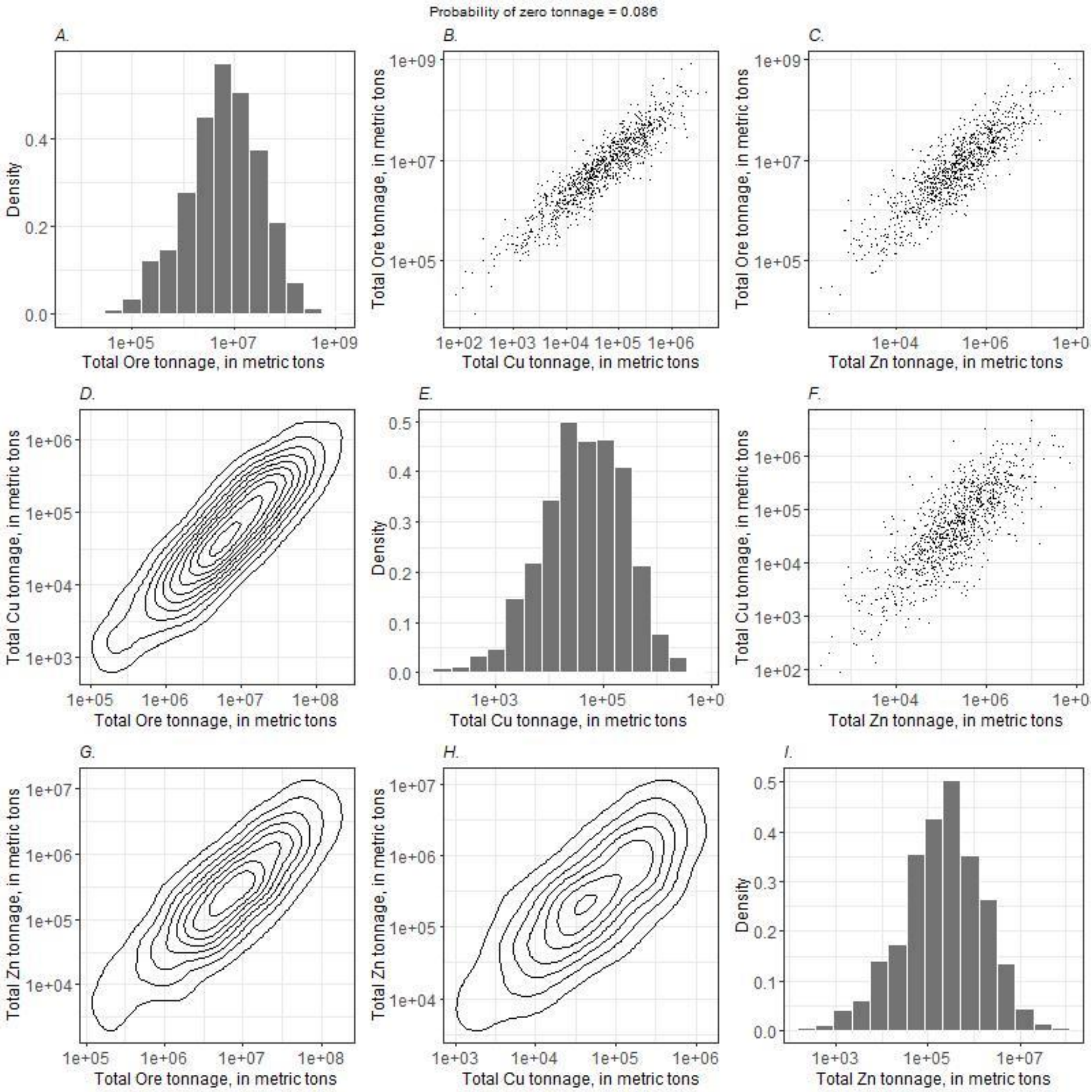

Figure 42: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

Economic Filter

The Economic filter tool estimates the proportion of the total estimated undiscovered resource that can be considered to be economically viable for mining. The tool applies simple engineering cost models to estimate the economic resource, and it is based on the USGS RAEF code (Shapiro & Robinson 2019).

The Economic filter tool RAEF process allows the same run options as the USGS RAEF software: a) Batch run using preset parameter file, b) interactive run using GUI input of parameters and c) empirical mode run.

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Input data for the filtering using interactive run (ref. Shapiro & Robinson 2019):
Tract area: Stekenjokk Tract 242 km^2
Simulated Deposits file: Monte Carlo Simulation Stekenjokk
Depth Intervals: 1; 0 - 1000 m and fraction 1
Deposit Type: Ore body massive/disseminated
Mine method: based on depth to the top of the deposit, if depth >= 61m: Block Caving, if depth < 61m: Open Pit
Mill type: 1 – Product flotation
Days of operation: 260 days
Marshall-Swift Cost updating index (MSC): 1.26
Investment rate of return: 0.15 (15 %)
Cap cost inflation factor: 1
Operating cost inflation factor: 1
CV_Cu, MRR_Cu: 3813.958, 0.91 (Commodity Value in 2008$/t, Metallurgical Recovery rate 91 %)
CV_Zn, MRR_Zn: 1851.864, 0.9 (Commodity Value in 2008$/t, Metallurgical Recovery rate 90 %)
Waste management options not chosen

Results:

Table 13: Summary statistics for in-ground contained resources and recovered resources (tonnages in Mt):

	means	min-max	median	std	P90	P70	P30	P10	Prob>=mean
Ore	17.71	0-267	5.72	49.83	0.0907	2.027	13.55	40.51	0.24125
Cu_con	0.158	0-43	0.041	0.564	0.000421	0.0134	0.103	0.350	0.21765
Zn con	0.949	0-225	0.196	3.659	0.00156	0.0576	0.529	1.976	0.19785
Cu rec	0.118	0-37	0.0153	0.483	0	0	0.063	0.272	0.206
Zn rec	0.769	0-192	0.116	3.123	0	0	0.395	1.624	0.19525
NPV_tr	4.43e08	0-5.4e10	56.8e07	1.38e09	0	0	2.53e08	1.08e09	0.21255

NPV_area: 1829240

Table 13 shows statistics for the deposit ore tonnage in million metric tons (Mt), contained in-ground mineral resource tonnage (Cu_con, Zn_Con, in Mt), recovered mineral resource tonnage (Cu_rec, Zn_rec, in Mt) and net present value of the tract (NPV_tr) in 2008$. The net present value pr km^2 is shown below the table; 1.83 mill $(2008)/km^2.

Table 14: Estimates of mean contained and recovered resources by commodity for the user-defined depth intervals (in Mt):

Depth interval	Cu_con_means	Cu_rec_means	Zn_con_means	Zn_rec_means	ProbOfZero
0-1000 m	0.158	0.118	0.949	0.769	0.5561

For the chosen depth interval 0-1000 m, Table 14 lists the mean statistics for the contained and recovered resources of Cu and Zn in million tons in the Stekenjokk tract.

The Economic Filter generates two graphs that show estimated ore deposit cutoff grade and recovered ore value as a function of ore tonnage, mine type, and deposit depth. In Figure 43, cutoff grade is expressed as copper equivalent grade (CuEQ%); in Figure 44, cutoff grade is expressed as ore value (in dollars per ton) based on the metallurgical recovery.

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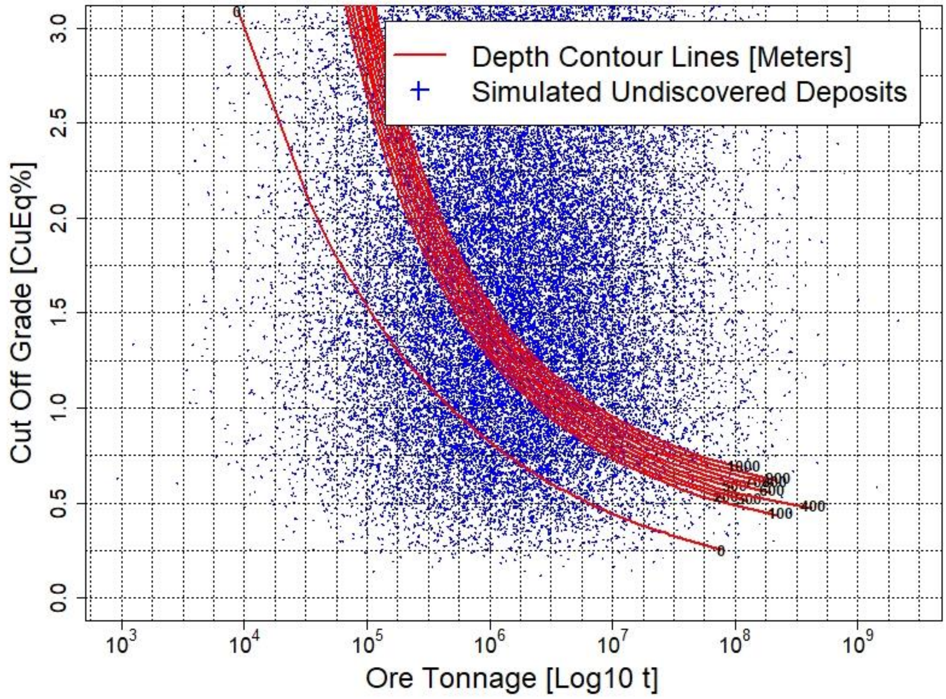

Figure 43: Copper equivalent (CuEQ%) grade/tonnage plot with cutoff grade versus deposit tonnage as a function of depth to top of the deposit in meters.

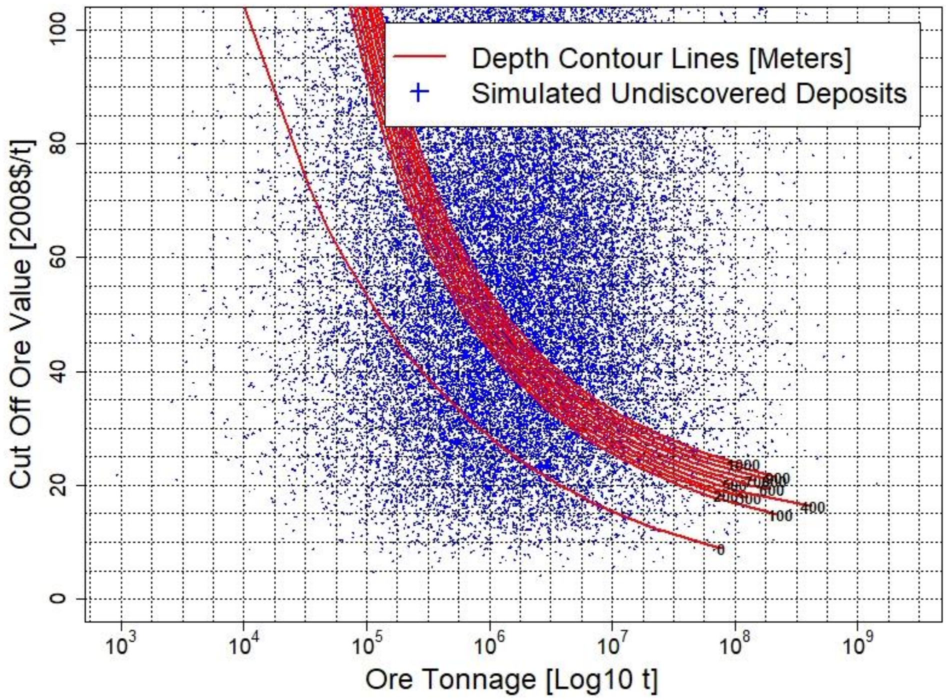

Figure 44: Ore value/tonnage plot with cutoff ore value versus deposit tonnage as a function of depth to top of the deposit in meters.

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Summary of the modelling for the Stekenjokk tract

Descriptive Model: VMS

Grade-Tonnage Model for bimodal-felsic VMS class: Mean (pdf): 0.68 % Cu, 2.99 % Zn, 7.22 Mt; Median (pdf): 0.66 % Cu, 2.98 % Zn, 1.44 Mt

Tract Delineation: The Stekenjokk Quartz-keratophyre unit in the Stikke nappe, area 242 km^2

Undiscovered deposits: VMS deposit density model gives 0 deposit @ N90, 1 deposit @ N50, 4 deposits @ N10. Expert data and negative binomial function: mean number of undiscovered deposits are 2.5

Monte Carlo Simulation – ore and resource tonnages in the undiscovered deposits: (mean) 17.7 Mt ore, 0.158 Mt Cu, 0.949 Mt Zn, (median) 5.72 Mt ore, 0.041 Mt Cu, 0.196 Mt Zn

Economic Filter (commodity value in 2008$/ton): mean value of tract 443 mill. $ (median 57 mill $), mean contained Cu 158 000 t and recovered Cu 118 000 t, mean contained Zn 949 000 t and recovered Zn 769 000 t.

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4.7. Assessment for the Blåsjö Tract

Description of the tract

The Blåsjön area is located in mountainous terrain (the Caledonides) in the westernmost part of County of Västerbotten, close to the border to Jämtland County and to Norway.
(Figure 45).

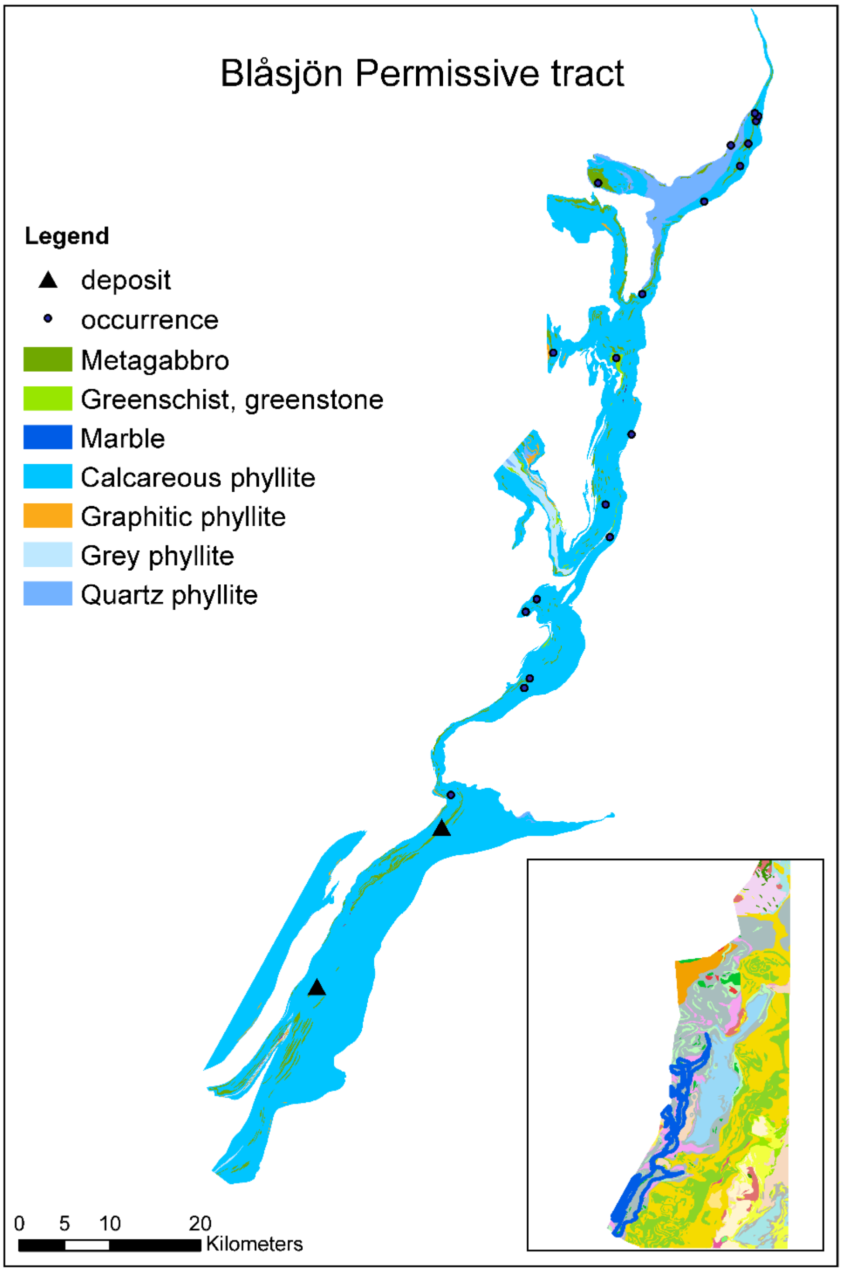

Figure 45: Geology of the Blåsjö tract, based on SGU bedrock database. Known mineralisations (from SGU ore database) are also shown.

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The Blåsjö phyllite (Nilsson 1964) consists of laminated, calcareous phyllite with sandy intercalations and occasional beds of graphitic phyllite. It was interpreted by Sjöstrand (1978) as a turbiditic shale-greywacke sequence. It contains numerous gabbro intrusions and has been used as a marker horizon that can be followed for more than 200 kilometres. The geochemical signature resembles ocean-floor basalt (Stephens 1980, Stephens et al. 1985). Sheets of albite trondhjemite with chilled margins have an intrusive age of c. 440 Ma (Claesson et al. 1988). The Blåsjö phyllite has been correlated with the Brakkfjället phyllite in the Leipikvattnet nappe (Stephens 1986a). The Blåsjö phyllite is the host to the Ankarvattnet massive sulphide deposit (Sundblad 1980).

Deposits and prospects in the Blåsjö tract

There are two known deposits within the Blåsjö tract, of which one of them has been mined in 1919 at the past (Jormlien) (Table 15).

Table 15: Deposit data for the Blåsjö tract

Name	east	north	Total tonnage	Host	Grade (%)	Reference
Jormlien	451380	7179562	0.612 Mt	calcareous metagreywacke	0.40 Cu, 4.75 Zn	SGU C 439; mink99001; brap81566; SGU Ca17; brap88005; SGU_ai_41
Ankarvattnet	465163	7197154	0.754 Mt	calcareous metagreywacke	0.45 Cu, 5.48 Zn	MiS 2; mink99001; brap00042;brap81566; brap81056; SGU_ai_74

Mt – million metric tons

The *Ankarvattnet deposit* was found in 1914 when extensive excavation work in the area made the ore's outcropping known. The partly outcropping ore have a sheet-like form with a diameter of 500 meters and 2-5 meters thick. Drilling in the 1950-60ies made it possible to define the resources to 750 000 t @ 0.45 % Cu, 5.48 % Zn, 0.37 % Pb and minor amounts of gold and silver. The ore can be divided into massive and disseminated mineralization and each type can be further divided into subtypes. Host rocks to the ore are calcareous phyllites and hydrothermally altered phyllites, the latter interpreted to be a stringer zone to the exhalative massive ore (Sundblad 1986). In the vicinity, but never in contact with the ore are gabbroic bodies that has been interpreted to be the heat source to the hydrothermal activity. Ore, host rocks and country rocks has been subjected to severe deformation.

The Jormlien deposit is around 1 km long and, on average 2 meter wide. Pyrrhotite-sphalerite ore is the dominant ore type followed by pyrite-sphalerite ore. In the structural hanging wall a chalcopyrite rich ore hosted in quartz-rich rocks are found. The ore is hosted by calcareous phyllites and hydrothermally altered phyllites. An ore estimate indicates 612 000 ton@ 0.4 % Cu and 4.8 % Zn.

In addition to the three deposits, there are 19 prospects and occurrences, which have been characterized as Siliciclastic-mafic VMS in the Blåsjö permissive tract. They are listed in Table 16.

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Table 16: Deposit data for prospects in the Blåsjö tract.

Name	east	north	Host rock	Cu (%)	Zn (%)	Pb (%)	Ag(g/t)	Au (g/t)	Sapling
Skidträskbäcken	499922	7275115	calcareous metagreywacke	0.7100	1.5300	0.04	7	<0.1	12 core samples
Skidträskbäcken N	500192	7275664	calcareous metagreywacke	0.4600	0.1000	0.07	3	3	3 core samples
Usmeten	498161	7270156	calcareous metagreywacke	1.2800	0.3100	<0.01	<5	<0.1	ore calc.
Abelvattnet	494200	7266247	calcareous metagreywacke	0.9000	0.0700	<0,01	<5	<0,1	ore calc.
Unna Gaisartjäkko	484485	7248938	calcareous metagreywacke	0.8000	0.5000	<0,01			Boliden
Svavelkismalmen	474497	7220919	calcareous metagreywacke	0.0200	0.0500	0.06	69	0.4	9 core sections
Marmere	499069	7272621	calcareous metagreywacke	0.1100	3.7900	2.98	53	0.1	2 samples
Skidträskbäcken W	499809	7275988	calcareous metagreywacke	1.1900	0.0300				1 sample
Daningen	477517	7249542	calcareous metagreywacke	9.8500	0.6000	0.002	12	0.6	2 samples
Naiträkk	482478	7268281	calcareous metagreywacke	1.7100	0.1100		5		8 ore boulders
Svilkisbäcken	487368	7256038	calcareous metagreywacke	0.3600	2.0500	0.04			8 samples
Saxän	475694	7222294	calcareous metagreywacke	0.6100	2.2800				3+2 ore samples
Tjopasi Västra	483785	7229165	calcareous metagreywacke	0.1000	1.2800	0.01			1 sample
Rautamavardo	483314	7232760	calcareous metagreywacke	1.6500	4.8000	0.03			1 sample
Aujoase	486176	7240529	quartz keratophyre	0.0000	0.0000				
Sjliengojaure 2	474324	7212515	calcareous metagreywacke	0.7500	0.0400	0.02			1 core sections
Sjliengojaure 1	474934	7213548	calcareous metagreywacke	0.1900	1.4200	0.02			3 core sections
Sarkenjaure	466209	7200681	calcareous metagreywacke	0.1800	0.9800	0.75	11		12 core sections
Kebnevardo	497155	7272442	calcareous metagreywacke	0.0000	0.0000				

Exploration data

In the Ankarvattnet area exploration commenced in 1914 with discovery of Ankarvattnet, Jormlien and other sulphide deposits (Tegengren 1924). For a short period, test-mining was done at Ankarvattnet.

In order to study correlation between the variation of apparent resistivity and different geological units shown in Figure 45, we have divided the area covered by the slingram into three smaller areas as shown in Figure 46.

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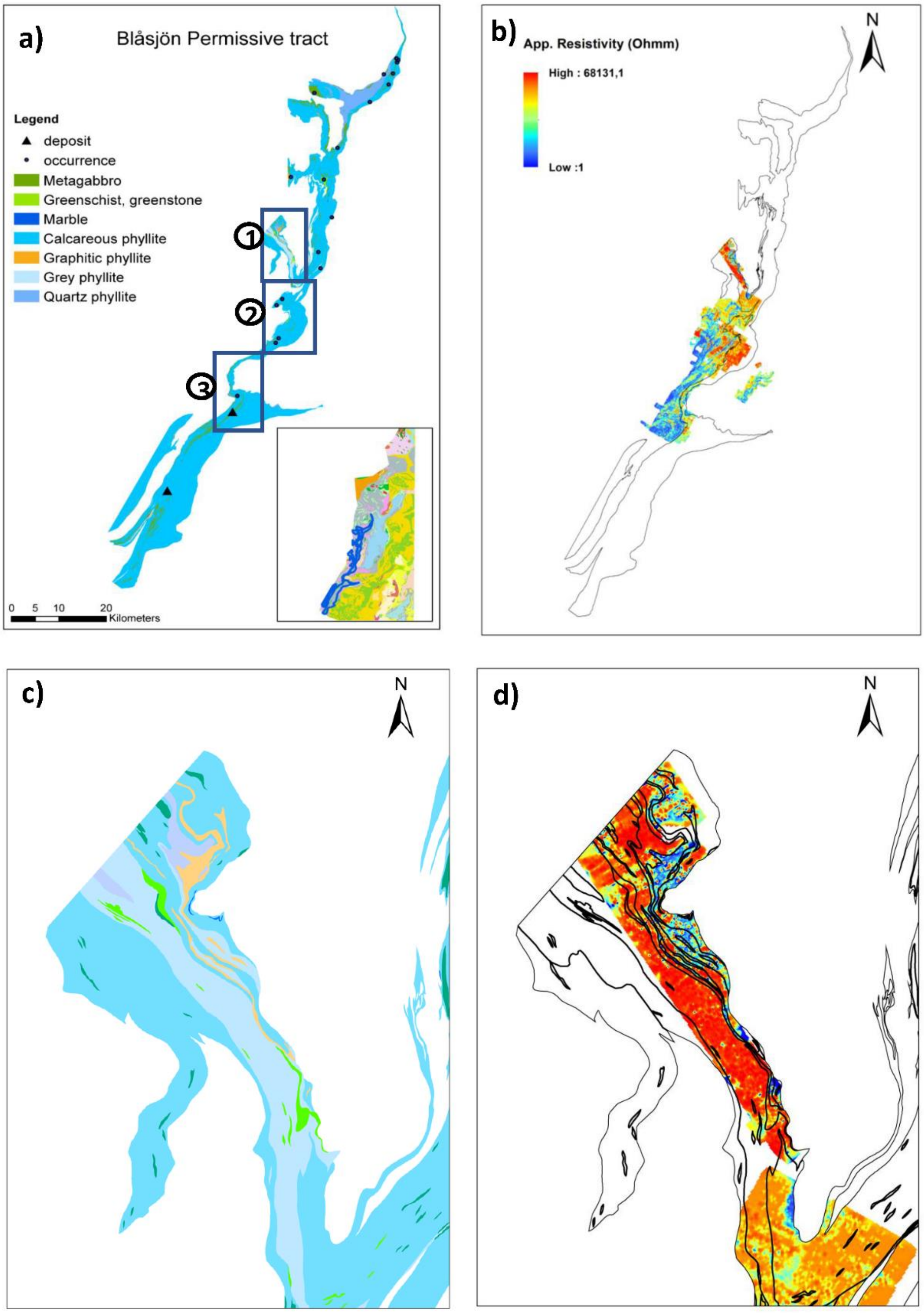

Figure 46: Location of smaller areas (1-3) for detailed demonstration of apparent resistivity data from the slingram measurements in the studied areas. a) location of subareas on the geological map, b) existing resistivity data in the entire area, c) geological map of subarea 1 and d) resistivity map in subarea 1. Note that the black polylines in (d) mark boundaries of various geological units shown in (c).

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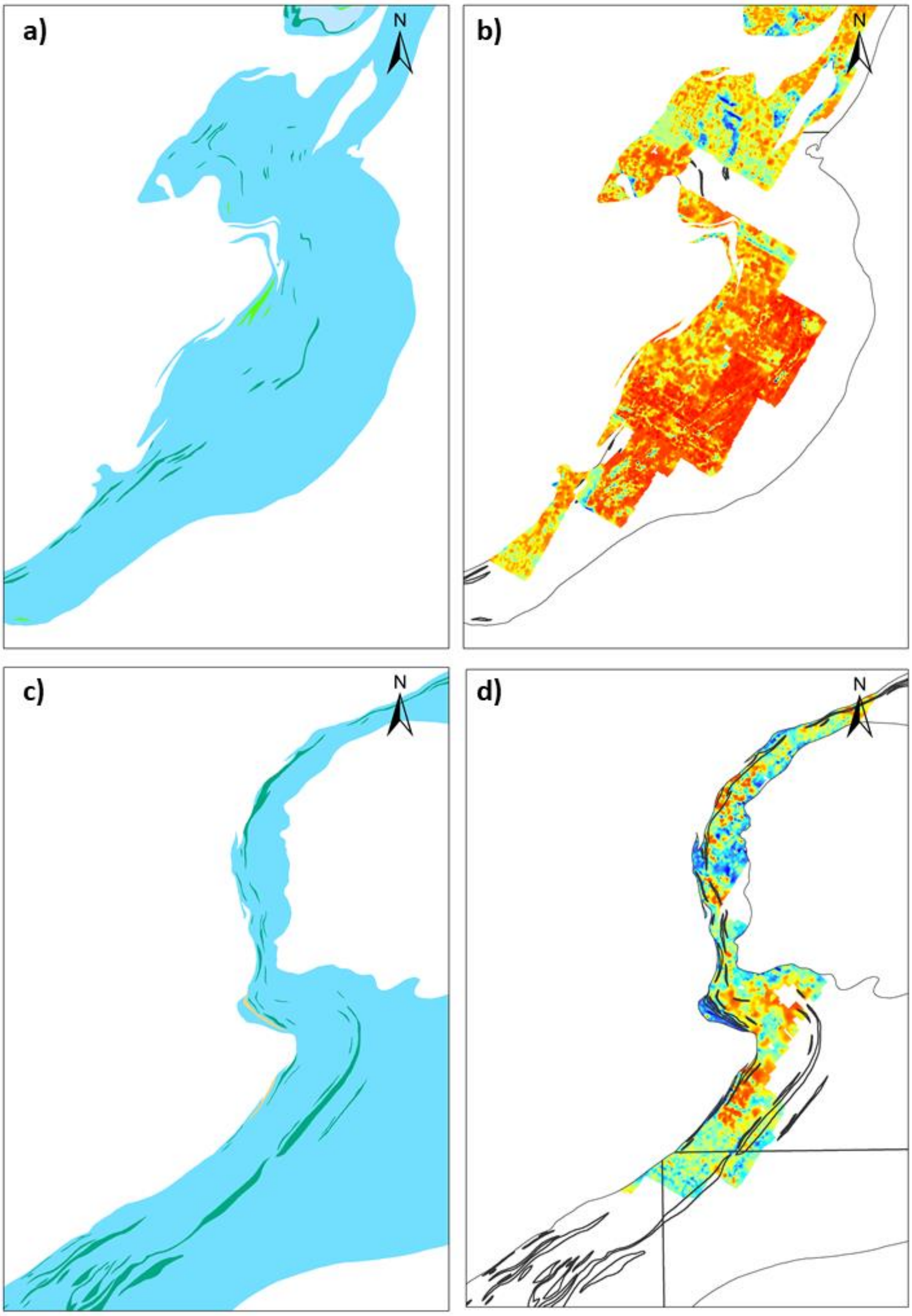

Figure 47: Comparison between the underlying geology (a & c) and the existing apparent resistivity data (b&d) in Subareas 2 and 3. For the location of subareas see Figure Figure 46a.

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In subarea 1 at the locations mapped as graphite phyllite (Figure 46c), the resistivity is considerably lower (< 10 Ohmm) by some orders of magnitudes compared to the areas mapped either as Calcareous phyllites/phyllites/Pelitic phyllites (Figure 46d). One should note that the single frequency-single spacing slingram method has a limited depth penetration and is mainly used for mapping purposes. A more detailed surveys with changing frequency-coil spacing can reveal more details of the variation of resistivity with depth. In subarea 2 (Figure 47 a,b), the resistivity is more homogeneous and has higher values compared to subarea 1. The geological map also shows a less variation and is mainly dominated by Calcarous phyllites (Figure 47a). There are a few spots where the resistivity shows lower values which might be related to the variation of thickness of the overburden as well as clay content in the sediments. In subarea 3 we observe the same trend as in subarea 1 where most of the low resistivity zones (Figure 47d) correlate strongly with occurrence of graphite phyllite (Figure 47c). In this subarea there is also a distinct low-resistivity zone observed in the south-easternmost part which overlaps with the mapped gabbroid-dioritoid. This might party indicate either the effect of fractured rocks, altered rocks or minor graphitic mineralization.

Modelling by the MAP Wizard

For the descriptive model, the VMS model was used (see section 3 and for the grade-tonnage model, data for the VMS siliciclastic-mafic subtype was used (section 4.3, dataset in appendix).

Grade-Tonnage model

1. Grade summary

Summary comparison of the pdf (probability density functions) representing the grades and the actual grades in the grade and tonnage model for the siliciclastic-mafic subclass of VMS deposits.

Pdf type: normal
Pdf is not truncated.
Number of discovered deposits in the grade and tonnage model: 60
Number of resources: 2

Quantiles (reported in percent)

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

	Component Cu		Component Zn		Component gangue	
	Gatm	Pdf	Gatm	Pdf	Gatm	Pdf
Minimum	0.02	0.00436	0.05	0.00066	87.6	6.02
0.25 quantile	0.50	0.41200	0.50	0.45000	94.3	94.80
Median	0.93	0.83100	1.70	1.22000	97.4	97.50
0.75 quantile	1.300	1.67000	4.50	3.25000	98.4	98.80
Maximum	5.00	56.50000	9.40	93.80000	99.9	100.00

Compositional mean (reported in percent).		
	Gatm	Pdf
Cu	0.847	0.847
Zn	1.230	1.230
gangue	97.900	97.900

Composite variation matrix			
	Cu	Zn	gangue
Cu	0.00	2.14	1.12
Zn	2.15	0.00	2.22
gangue	1.12	2.22	0.00

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

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The composite variation matrix has two parts: its upper triangle and its lower triangle. The upper triangle is the upper triangle of the variation matrix for the actual grades in the grade and tonnage model. The lower triangle is the lower triangle of the variation matrix for the pdf that the represents the grades. Thus, corresponding elements in the upper and lower triangles should be compared to one another.

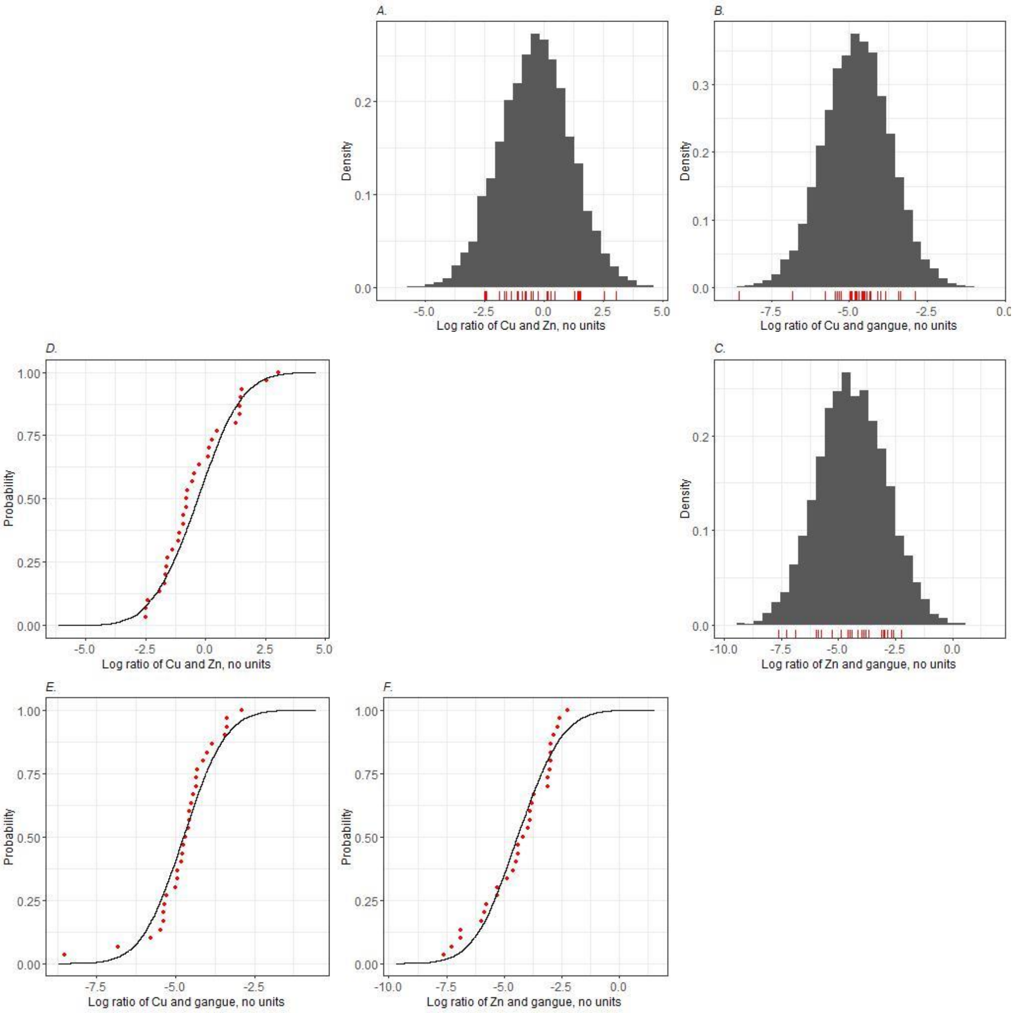

Figure 48: Histograms and cumulative distribution functions, calculated from the probability density function representing the grades. In A-C, vertical red lines (bottom) represent the log-ratios calculated from the grade-tonnage model. in D-F, the red dots are empirical distribution functions for the log-ratios calculated from the grade-tonnage model.

<u>2. Tonnage summary</u>

Summary comparison of the pdf representing the tonnage and the actual tonnages in the model for VMS deposits of the siliclastic-mafic subclass.

Pdf type: normal

Pdf is not truncated.

Number of discovered deposits in the model: 60

Deviance = -18.7131

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The left table pertains to the log-transformed tonnages. Column Gatm refers to the actual tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.
The right table pertains to the (untransformed) tonnages. Column Gatm refers to the tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

	Gatm	Pdf
Minimum	9.55	4.29
0.25 quantile	11.90	11.90
Median	13.40	13.20
0.75 quantile	14.00	14.40
Maximum	16.80	21.60
Mean	13.20	21.60
St. deviation	1.82	1.82

	Gatm	Pdf
Minimum	14000	72.8
0.25 quantile	150000	152000
Median	631000	517000
0.75 quantile	1180000	1760000
Maximum	19100000	2400000000
Mean	2370000	2680000
St. deviation	4810000	12900000

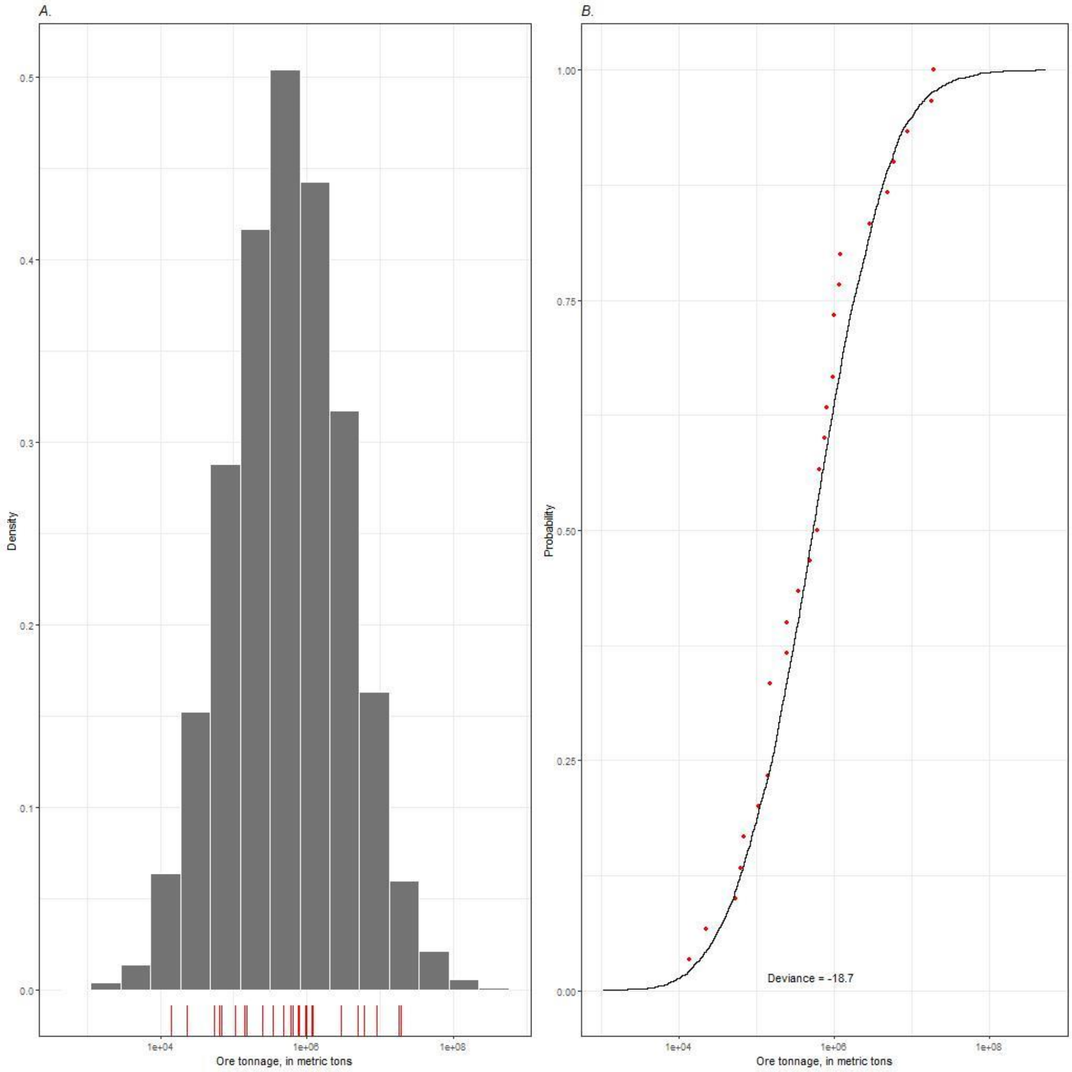

Figure 49: A) Probability density function that represents the ore tonnage in an undiscovered deposit. Vertical lines at the bottom represent the ore tonnages from the grade-tonnage model. B) Corresponding cumulative distribution function (solid line). The red dots are the empirical cumulative distribution function for the ore tonnages from the grade-tonnage model.

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Tract delineation

The Blåsjö tract is restricted by the Blåsjö phyllite unit. Because there are limited other data than geology covering the tract, the Tract Delineation Tool in MAP Wizard has not been used for the Blåsjö tract.

Undiscovered deposits

1. Deposit density model

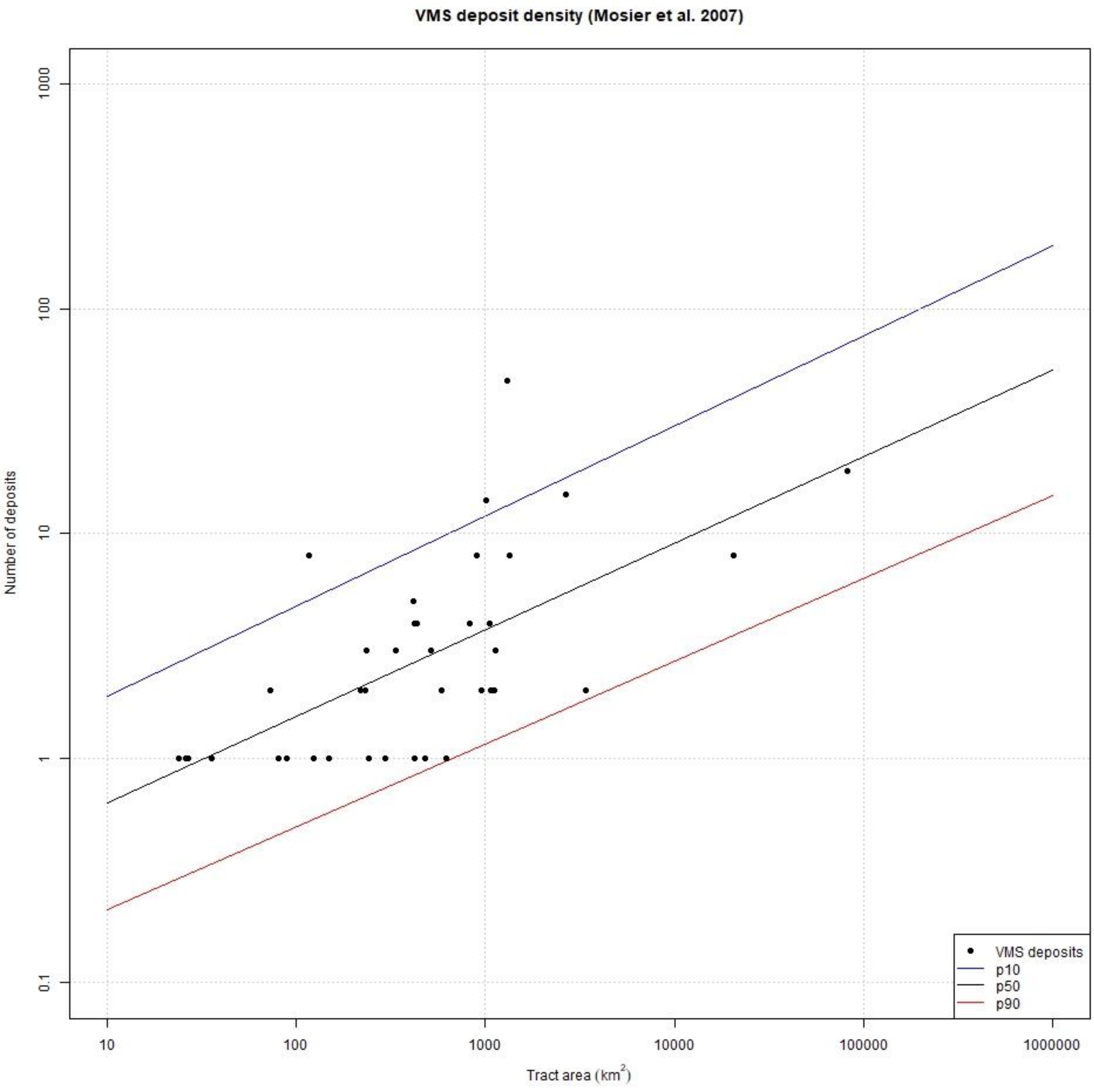

Figure 50: Plot of the VMS deposit density by Mosier et al. (2007).

Excluding the intrusives, which are postgenetic to the VMS deposits (see above), the Blåsjö tract has an area of 801 km^2, which based on the VMS deposit density model by Mosier et al. (2007, Figure 50) gives a probability of N90: 1 deposits, N50: 2 deposit, N10: 5 deposits.

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2. Negative binomial function and expert data

Expert	N90	N50	N10
AH	3	5	8
KSA	1	2	8
STB	1	2	5
MST	1	3	5
KSU	1	2	4
BK	0	2	5
TG	1	3	5
MS	1	3	6
HS	1	2	4
KR	1	3	6
TB	2	5	10
JSS	1	2	4
OO	1	2	4

Summary of pmf, number of undiscovered deposits	
Type	NegBinomial
Mean	2.43922
Variance	2.43686
St. Dev.	1.56104
Mode	2
Smallest N deposits in pmf	0
Largest N deposits in pmf	9
Inform. entropy	1.81697

Expert estimates of deposits in the Blåsjö tract at 0.90, 0.50 and 0.10 probability and the resulting summary statistics for the probability mass function using the negative binomial option.

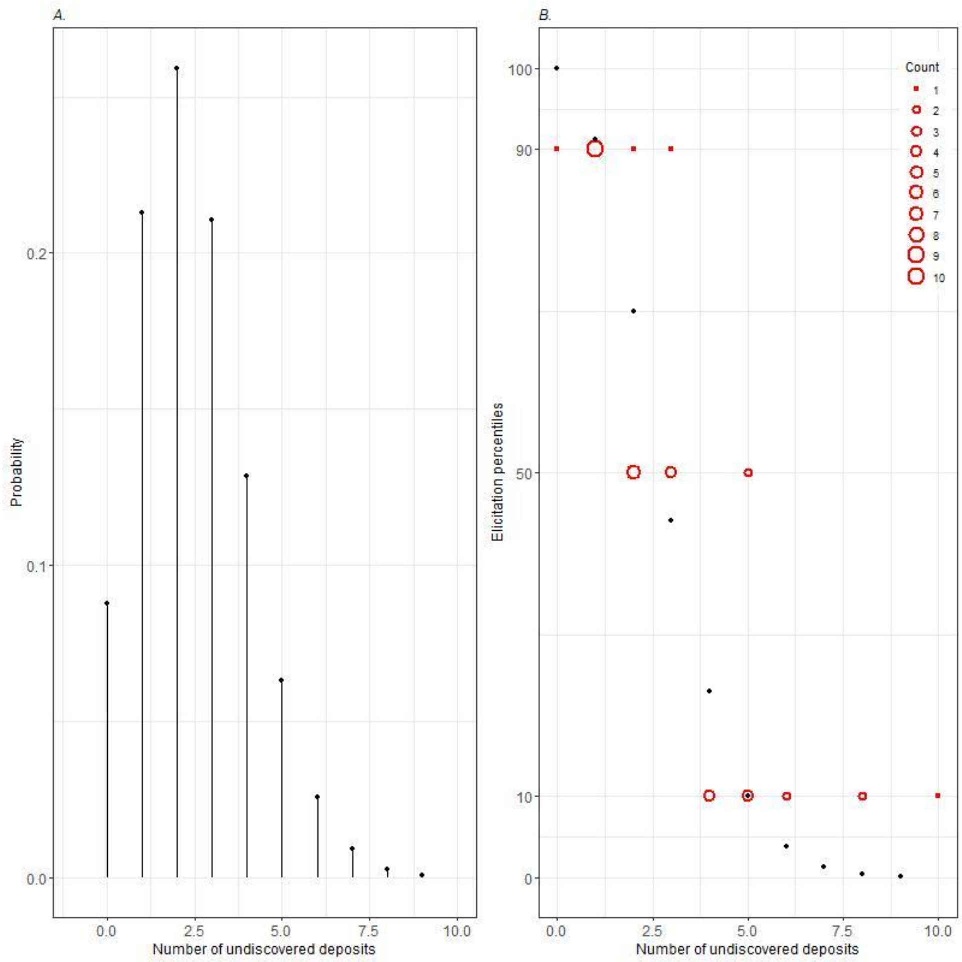

Figure 51 (left): Plot of the estimated probability mass function (pmf) using the negative binomial option. (Right): The corresponding cumulative distribution function with the expert estimates (red circles).

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Monte Carlo Simulation with Caledonian VMS siliciclastic-mafic Grade-Tonnage model

Summary of the pdf for the total ore and resource tonnages in all undiscovered deposits within the permissive tract.

Ore, Cu, Zn (in Mt):

	0.05q	0.1q	0.25q	0.5q	0.75q	0.9q	0.95q	Mean	P (0)	P(>mean)
Ore	0	0.222	0.469	2.000	6.180	14.90	25.30	6.530	0.0912	0.240
Cu	0	0.000122	0.00372	0.0189	0.0666	0.190	0.343	0.087	0.0912	0.205
Zn	0	0.000118	0.00501	0.0304	0.1240	0.385	0.773	0.199	0.0912	0.179

Explanation

" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix			
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn
Ore	6.530	6.530	Ore	18.90	20.60	Ore	NA	0.711	0.544
Cu	0.087	0.090	Cu	0.339	0.428	Cu	0.646	NA	0.437
Zn	0.199	0.202	Zn	0.870	1.280	Zn	0.516	0.419	NA

Explanation

1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.
2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

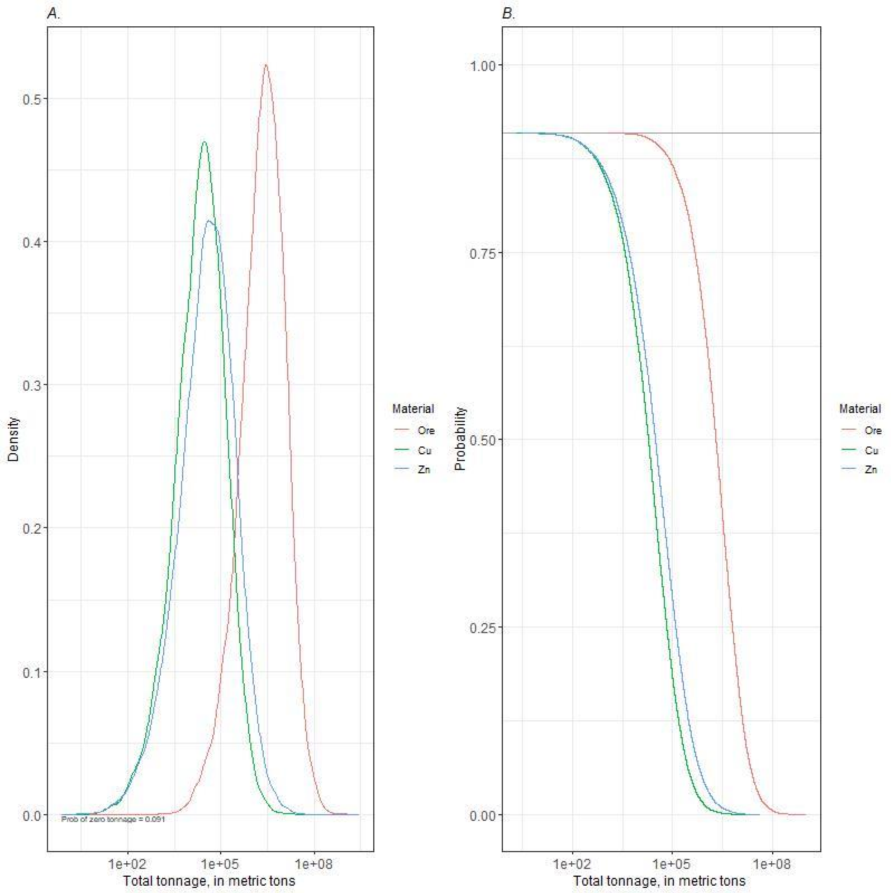

Figure 52: Plots of A) univariate marginal probability density functions and B) cumulative distribution functions for total ore Cu and Zn tonnages in the undiscovered deposits.

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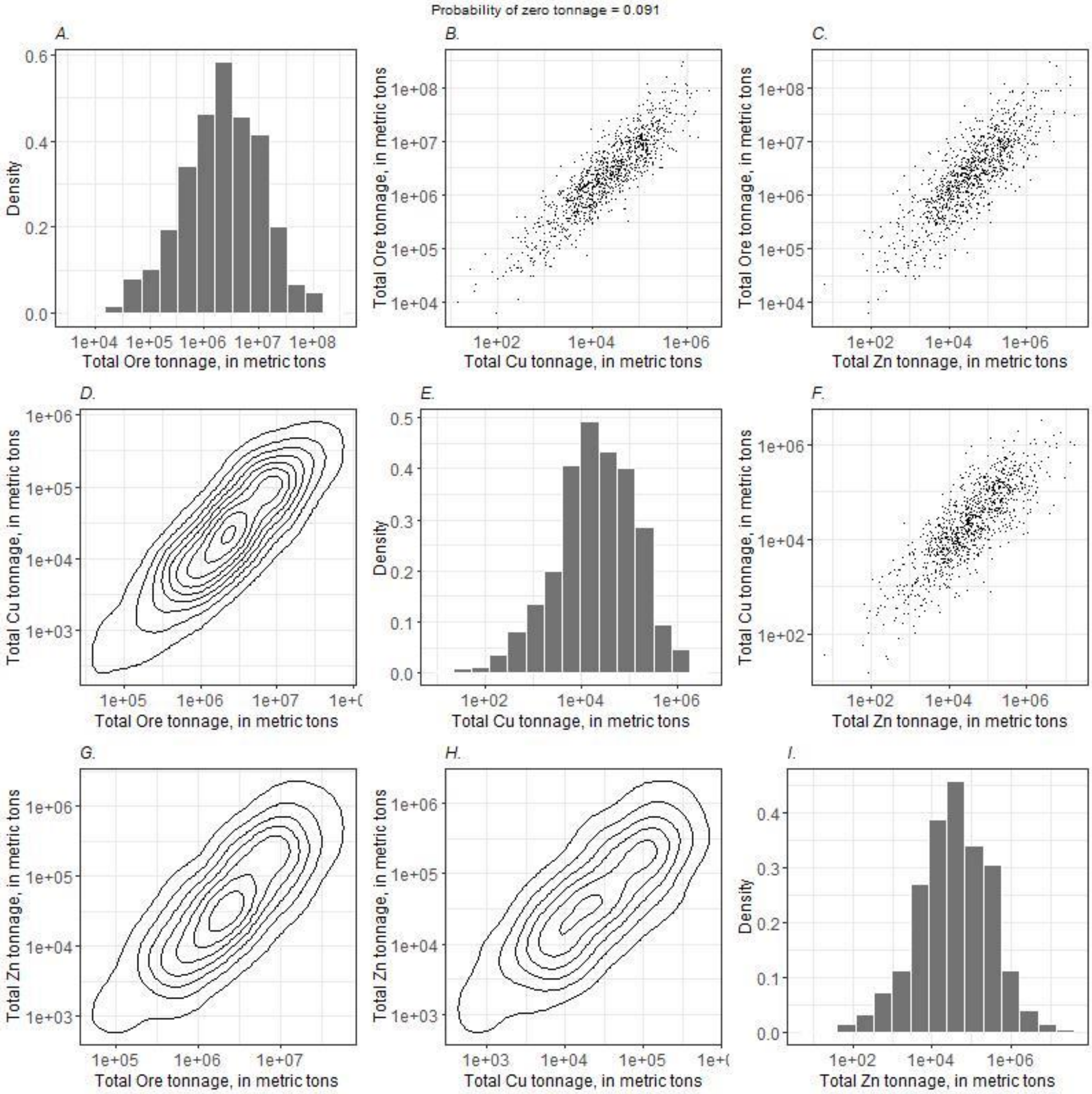

Figure 53: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

Economic Filter

The Economic filter tool estimates the proportion of the total estimated undiscovered resource that can be considered to be economically viable for mining. The tool applies simple engineering cost models to estimate the economic resource, and it is based on the USGS RAEF code (Shapiro & Robinson 2019).

The Economic filter tool RAEF process allows the same run options as the USGS RAEF software: a) Batch run using preset parameter file, b) interactive run using GUI input of parameters and c) empirical mode run.

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Input data for the filtering using interactive run (ref. Shapiro & Robinson 2019):

Tract area: Blåsjö Tract 801 km^2
Simulated Deposits file: Monte Carlo Simulation Blåsjö
Depth Intervals: 1; 0 - 1000 m and fraction 1
Deposit Type: Ore body massive/disseminated
Mine method: based on depth to the top of the deposit, if depth >= 61m: Block Caving, if depth < 61m: Open Pit
Mill type: 1 – Product flotation
Days of operation: 260 days
Marshall-Swift Cost updating index (MSC): 1.26
Investment rate of return: 0.15 (15 %)
Cap cost inflation factor: 1
Operating cost inflation factor: 1
CV_Cu, MRR_Cu: 3813.958, 0.91 (Commodity Value in 2008$/t, Metallurgical Recovery rate 91 %)
CV_Zn, MRR_Zn: 1851.864, 0.9 (Commodity Value in 2008$/t, Metallurgical Recovery rate 90 %)
Waste management options not chosen

Results:

Table 17: Summary statistics for in-ground contained resources and recovered resources (tonnages in Mt):

	means	min-max	median	std	P90	P70	P30	P10	Prob>=mean
Ore	6.472	0- 1330	2.016	20.62	0.0196	0.6908	4.791	146.229	0.23495
Cu_con	0.0895	0- 61	0.0189	0.552	99e-6	0.00559	0.0493	0.1832	0.1962
Zn con	0.1968	0- 122	0.0298	1.256	91e-6	0.00801	0.0905	0.3810	0.17595
Cu rec	0.0630	0- 53	0	0.476	0	0	0.0209	0.1310	0.1741
Zn rec	0.1480	0-104	0	1.071	0	0	0.0447	0.2901	0.1656
NPV_tr	1.36e08	5.4e10	0	7.52e08	0	0	3.68e07	2.98e08	0.17335

NPV_area: 169382

Table 17 shows statistics for the deposit ore tonnage in million metric tons (Mt), contained in-ground mineral resource tonnage (Cu_con, Zn_Con, in Mt), recovered mineral resource tonnage (Cu_rec, Zn_rec, in Mt) and net present value of the tract (NPV_tr) in 2008$. The net present value pr km^2 is shown below the table; 169382 $(2008)/$km^2$.

Table 18: Estimates of mean contained and recovered resources by commodity for the user-defined depth intervals (in Mt):

Depth interval	Cu_con_means	Cu_rec_means	Zn_con_means	Zn_rec_means	ProbOfZero
0-1000 m	0.0895	0.0630	0.1968	0.1480	0.747

For the chosen depth interval 0-1000 m, Table 18 lists the mean statistics for the contained and recovered resources of Cu and Zn in million tons in the Blåsjö tract.

The Economic Filter generates two graphs that show estimated ore deposit cutoff grade and recovered ore value as a function of ore tonnage, mine type, and deposit depth. In Figure 54, cutoff grade is expressed as copper equivalent grade (CuEQ%); in Figure 55, cutoff grade is expressed as ore value (in dollars per ton) based on the metallurgical recovery.

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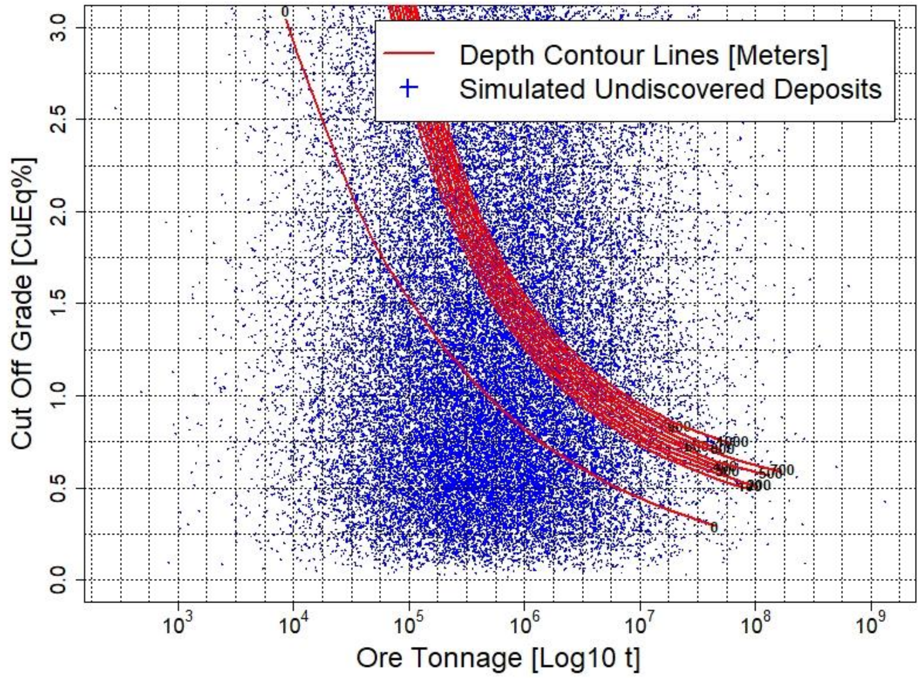

Figure 54: Copper equivalent (CuEQ%) grade/tonnage plot with cutoff grade versus deposit tonnage as a function of depth to top of the deposit in meters.

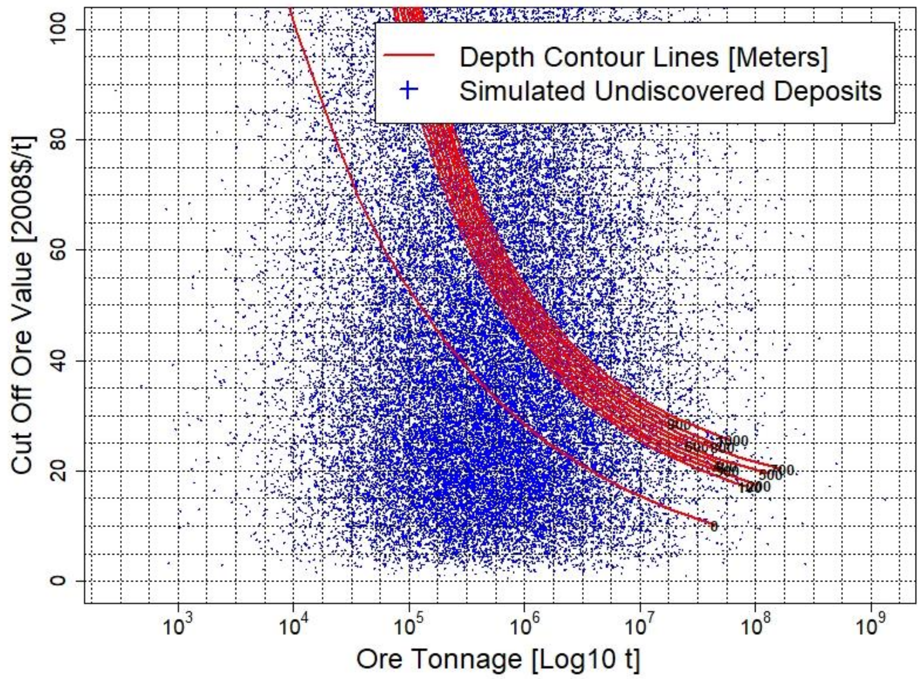

Figure 55: Ore value/tonnage plot with cutoff ore value versus deposit tonnage as a function of depth to top of the deposit in meters.

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Summary of the modelling for the Blåsjö tract

Descriptive Model: VMS

Grade-Tonnage Model for siliciclastic-mafic VMS class: Mean (pdf): 0.85 % Cu, 1.23 % Zn, 2.68 Mt; Median (pdf): 0.83 % Cu, 1.22 % Zn, 0.517 Mt

Tract Delineation: The Blåsjö phyllie unit, area 801 km^2

Undiscovered deposits: VMS deposit density model gives 1 deposit @ N90, 2 deposit @ N50, 5 deposits @ N10. Expert data and negative binomial function: mean number of undiscovered deposits are 2.4

Monte Carlo Simulation – ore and resource tonnages in the undiscovered deposits:
(mean) 6.53 Mt ore, 0.087 Mt Cu, 0.199 Mt Zn, (median) 2.00 Mt ore, 0.019 Mt Cu, 0.030 Mt Zn

Economic Filter (commodity value in 2008$/ton): mean value of tract 136 mill. $, mean contained Cu 89 500 t and recovered Cu 63 000 t, mean contained Zn 196 800 t and recovered Zn 148 000 t.

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References

Claesson, S., Stephens, M.B. & Klingspor, I., 1988: U–Pb zircon dating of felsic intrusions, Middle Köli Nappes, central Scandinavian Caledonides. Norwegian Journal of Geology 68, 89–97.

Eilu, P., Bergman, T., Bjerkgård, T., Feoktistov, V., Hallberg, A., Korsakova, M., Krasotkin, S., Muradymov, G., Nurmi, P. A., Often, M., Perdahl, J-A., Philippov, N., Sandstad, J.S., Stromov, V. and Tontti, M., 2009: Metallogenic Map of the Fennoscandian Shield, 1:2 000 000. Geological Survey of Finland, Geological Survey of Norway, Geological Survey of Sweden, The Federal Agency of Use of Mineral Resources of the Ministry of Natural Resources and Ecology of the Russian Federation.

Geovista, 2013: Technical report: Skiftesmyr – Mineral resource estimate. 69 p.

Grenne, T., 1995: Kjerneboring i Godejord 1994. Norges geologiske undersøkelse Rapport 95.101. 22 p. (in Norwegian).

Grenne, T. and Erichsen, E. 1996. 3D-modellering, tonnasje- og gehaltberegning av Godejordforekomsten, Grong, Nord-Trøndelag. Norges geologiske undersøkelse Rapport 96.024. 41 p. (in Norwegian).

Grenne, T., Ihlen, P.M. and Vokes F.M., 1999: Scandinavian Caledonide metallogeny in a plate tectonic perspective. Mineralium Deposita 34, p. 422-471.

Grenne, T., Heim, M., Reinsbakken, A. & Sandstad, J.S., 2000: Arc rifting and ore formation in the Early Ordovician Skorovass complex, Central Norway. 24. Nordiske geologiske vintermøtet, Trondheim 2000. Geonytt nr. 1.

Högbom, A., 1925, De geologiska förhållandena inom Stekejokk-Remdalens malmtrakt, SGU C 329, 96 p.

Nilsson, G., 1964: Berggrunden inom Blåsjöområdet i nordvästra Jämtlandsfjällen. Sveriges geologiska undersökning C 595, 70 pp.

Odling, N.E. 1988: Deformation of the Joma sulphide deposit, Caledonides of Nord-Trøndelag, Norway. In: Zachrisson, E. (ed.) Proceedings of the 7th Quadrennial IAGOD Symposium, Luleå, Sweden. Stuttgart: E. Schweizerbart'sche, Verlagsbuchhandlung, p. 513–524.

Reinsbakken, A., 1986: The Joma Cu-Zn massive sulphide deposit hosted by mafic metavolcanic rocks. In: Stephens M.B. (ed.) Stratabound sulphide deposits in the central Scandinavian Caledonides. Sveriges Geol. Undersökning Ca 60, p. 50–54.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Reinsbakken, A., 1992: The Skorovass volcanogenic massive sulphide deposit – volcanostratigraphy, petrochemistry, hydrothermal alteration and paleotectonic setting. Dr.ing. Thesis, UNIT–NTH. 363 p.

Sandstad, J. S., Reinsbakken, A. & Grenne, T., 1997: The Skorovass complex, Central Norwegian Caledonides: Massive sulphides in an Early Ordovician immature arc setting. F. M. Vokes Anniversary Symposium, Trondheim, Norway.

Sandstad, J.S., Bjerkgård, T., Boyd, R., Ihlen, P., Korneliussen, A., Nilsson, L.P., Often, M., Eilu, P. and Hallberg, A., 2012: Metallogenic areas in Norway. In Eilu, P. (ed): Mineral deposits and metallogeny of Fennoscandia. Geological Survey of Finland, Special Paper 53, p. 35-138.

Shanks, W.C. Pat, III and Thurston, R., eds., 2012: Volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070–C, 345 p.

Sjöstrand, T., 1978: Caledonian geology of the Kvarnbergsvattnet area, northern Jämtland, central Sweden. Sveriges geologiska undersökning C 735, 107 p.

Stephens, M.B., 1980: Occurrence, nature and tectonic significance of volcanic and high-level intrusive rocks within the Swedish Caledonides. In: Wones, D.R. (ed.) The Caledonides in the U.S.A. Virginia Polytechnic and State University, Department of Geological Sciences Memoirs 2, 289–298.

Stephens, M. B., 1982: Field relationships, petrochemistry and petrogenesis of the Stekenjokk volcanites, central Swedish Caledonides. Sver. geol. undersökning C 786, 111 p.

Stephens, M.B.,1986a: Metallogeny of stratabound sulphide deposits in the central Scandinavian Caledonides. In: Stephens, M.B. (ed.) Stratabound sulphide deposits in the Central Scandinavian Caledonides. Sveriges geologiska undersökning Ca 60, p. 24–29.

Stephens, M. B., 1986b: Stratigraphy and deformation in the massive sulphide-bearing Stikke nappe, Upper Allochthon. In: Stephens, M. B. (ed.) Stratabound sulphide deposits in the Central Scandinavian Caledonides. Sver. geol. unders. Ca 60, 5–16.

Stephens, M.B., 2020: Upper and uppermost thrust sheets in the Caledonide orogen, Sweden: outboard oceanic and exotic continental terranes. In: Stephens, M.B. & Bergman Weihed, J. (eds) 2020. Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources. Geological Society, London, Memoirs, 50, 549575. https://doi.org/10.1144/M50-2019-12

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Stephens, M.B., Furnes, H., Robins, B. & Sturt, B.A. 1985: Igneous activity within the Scandinavian Caledonides. In: Gee, D.G. & Sturt, B.A. (eds) The Caledonide Orogen – Scandinavia and Related Areas. John Wiley and Sons, Chichester, UK, 623–656.

Sundblad, K. & Gee, D. G. 1984: Occurrence of a uraniferous-vanadiniferous graphitic phyllite in the Köli Nappes of the Stekenjokk area, central Swedish Caledonides. Geologiska Föreningens i Stockholm Förhandlingar 106, 269–274.

Sundblad, K., 1980: A tentative "volcanogenic" formation model for the sediment-hosted Ankarvattnet Zn-Cu-Pb massive sulphide deposit, central Swedish Caledonides. Norges geologiske undersøkelse 360, 211–227.

Sundblad, K., 1986. The metasediment-hosted Ankarvattnet massive sulphid deposit. In: Stephens, M. B. (ed.) Stratabound sulphide deposits in the Central Scandinavian Caledonides. Sveriges geologiska undersökning Ca 60, 30-33.

Sundblad, K., Zachrisson, E., Smeds, S.-A., Berglund, S. & Ålinder, C.,1984: Sphalerite geobarometry and arsenopyrite geothermometry applied to metamorphosed sulfide ores in the Swedish Caledonides. Economic Geology 79, 1660–1668.

Tegengren, F. R., 1924, Sveriges ädlare malmer och bergverk, SGU Ca 17.

Zachrisson, E.,1964: The Remdalen Syncline. Sver. geologiska undersökning C 596, 53 p.

Zachrisson, E.,1969: Caledonian geology of northern Jämtland– southern Västerbotten. Sveriges geologiska undersökning C 644, 33 p.

Zachrisson, E. 1971, The structural setting of the Stekenjokk Ore Bodies, Central Swedish Caledonides. Economic Geology vol. 66, p. 641-652.

Zachrisson, E. 1984. Lateral Metal Zonation and Stringer Zone Development, Reflecting Fissure-Controlled Exhalations at the Stekenjokk-Levi Strata-Bound Sulfide Deposit, Central Scandinavian Caledonides, Economic Geology vol 79, p. 1643-1659.

Zachrisson, E.,1986a: The Stekenjokk Zn-Cu(-Pb) massive sulphide deposit in a bimodal meta-volcanic sequence. In: Stephens, M.B. (ed.) Stratabound sulphide deposits in the Central Scandinavian Caledonides. Sver. geologiska undersökning Ca 60, p. 34–41.

Zachrisson, E. 1986b: The structural setting of the Stekenjokk ore bodies, Central Swedish Caledonides. Economic Geology 66, 641–652.

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5. VMS assessment in the Skellefte District

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[(1)] Geological Survey of Sweden
[(2)] Geological Survey of Norway

5.1. Introduction

The Skellefte district (Allen et al. 1996; Kathol & Weihed 2005) is one of four major ore-provinces, of which three are currently ore-producing in Sweden (Figure 56). The other regions are Bergslagen (Stephens et al. 2009), the Northern Norrbotten ore province (Bergman et al. 2001, Bergman 2018) and the Caledonian orogen. The Skellefte district with surrounding areas is situated in northern Västerbotten and southern Norrbotten counties.

The bedrock in the Skellefte district was formed or reworked by Svecokarelian orogenic processes, which lasted from about 1.96 to 1.75 Ga. This time interval includes subduction-related processes, collision, and extension-related collapse of the thickened crust. The peak of Svecokarelian deformation and metamorphism occurred between 1.85 and 1.80 Ga (Stephens et al. 1997), but earlier phases of deformation at 1.89 – 1.87 Ga have under the last decade been reported by Skyttä et al. (2012a, b).

The Svecokarelian orogen comprises Svecokarelian intrusive rocks, formed by orogenic processes and Svecofennian supracrustal rocks, i.e., early orogenic sedimentary and volcanic rocks, the latter hosting the VMS deposits of the Skellefte district.

The Skellefte district in a wide sense (Kathol et al. 2005; Figure 57) is situated in the transition area between the Bothnian Basin (Hietanen 1975) in the south, and areas consisting mainly of subaqueous marine and subaerial volcanic arc assemblages in the north. Marine, mainly epiclastic supracrustal rocks of the basin are grouped under the name Bothnian Supergroup, whereas the volcanic arc assemblages are divided into the subaqueous Skellefte and Vargfors groups and the subaerial Arvidsjaur Group. Within the volcanic arc–Bothnian Basin transition zone, epiclastic, commonly turbiditic sedimentary rocks are interpreted to interfinger with subaqueous volcanic rocks of the Skellefte Group and sedimentary rocks of the Vargfors Group.

Upwards and laterally to the north, the Skellefte Group rocks pass into mainly subaerial volcanic sequences of the Arvidsjaur Group. The marine equivalent of the Arvidsjaur Group is the Vargfors Group, which consists mainly of coarse clastic and turbiditic sedimentary rocks and mafic volcanic rocks, deposited on the rocks of the Skellefte and Bothnian groups or the lower parts of the Arvidsjaur Group. Differences between the Skellefte, Vargfors, and Bothnian groups are indicated

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by different geochemical affinities of basic volcanic rocks. However, as these rocks occur only sparsely, especially within the Bothnian Supergroup, the boundary between the Skellefte and Vargfors groups on the one hand and the Bothnian Supergroup on the other is drawn somewhat arbitrarily on the map (Kathol et al. 2005, Kathol & Weihed 2005).

This artificial line is generally interpreted as a lateral transition from one group to the other. Rocks of the Skellefte and Vargfors groups have their coeval counterparts within the Bothnian Supergroup. In places, the Skellefte/Bothnian groups or Vargfors/Bothnian groups contain laterally equivalent rock associations. In terms of sequence stratigraphy these associations should be considered as one unit, which probably consists of several, individual sequences.

At different stages and at different levels throughout the sedimentary and volcanic evolution within the Skellefte district and surrounding areas, the supracrustal rocks have been intruded by voluminous amounts of intrusive rocks. On the one hand, these intrusions enable dating of the sedimentary record; on the other hand, they obscure primary relationships between different supracrustal units.

5.2. Exploration and discovery history of VMS deposits

This chapter is taken in a shorter somewhat simplified version from the chapter 'Mineral deposit discovery history' in Kathol & Weihed (2005). For a more detailed exploration history see the particular chapters for the western, central and eastern Skellefte district.

The record of mineral exploration dates back to the early eighteenth century. The brief historical outline of pre-modern mining below is based largely on the summary presented in Tegengren & Johansson (1924). The first record of mining is from 1704 when copper ore was mined in the north-eastern part of the Skellefte district. Sporadic short-lived trial mining seems to have prevailed throughout the eighteenth century. Around 1850 attempts were made to mine silver in Skellefteå. In early 1900 gold was discovered in the southeastern part of the Skellefte district and this resulted in intensified exploration in the area. Several minor gold-arsenic mineralizations were discovered as well as iron-copper sulphide mineralizations. However, none of the mineralizations were found to be economically worthwhile and in 1908, only one claim was still held.

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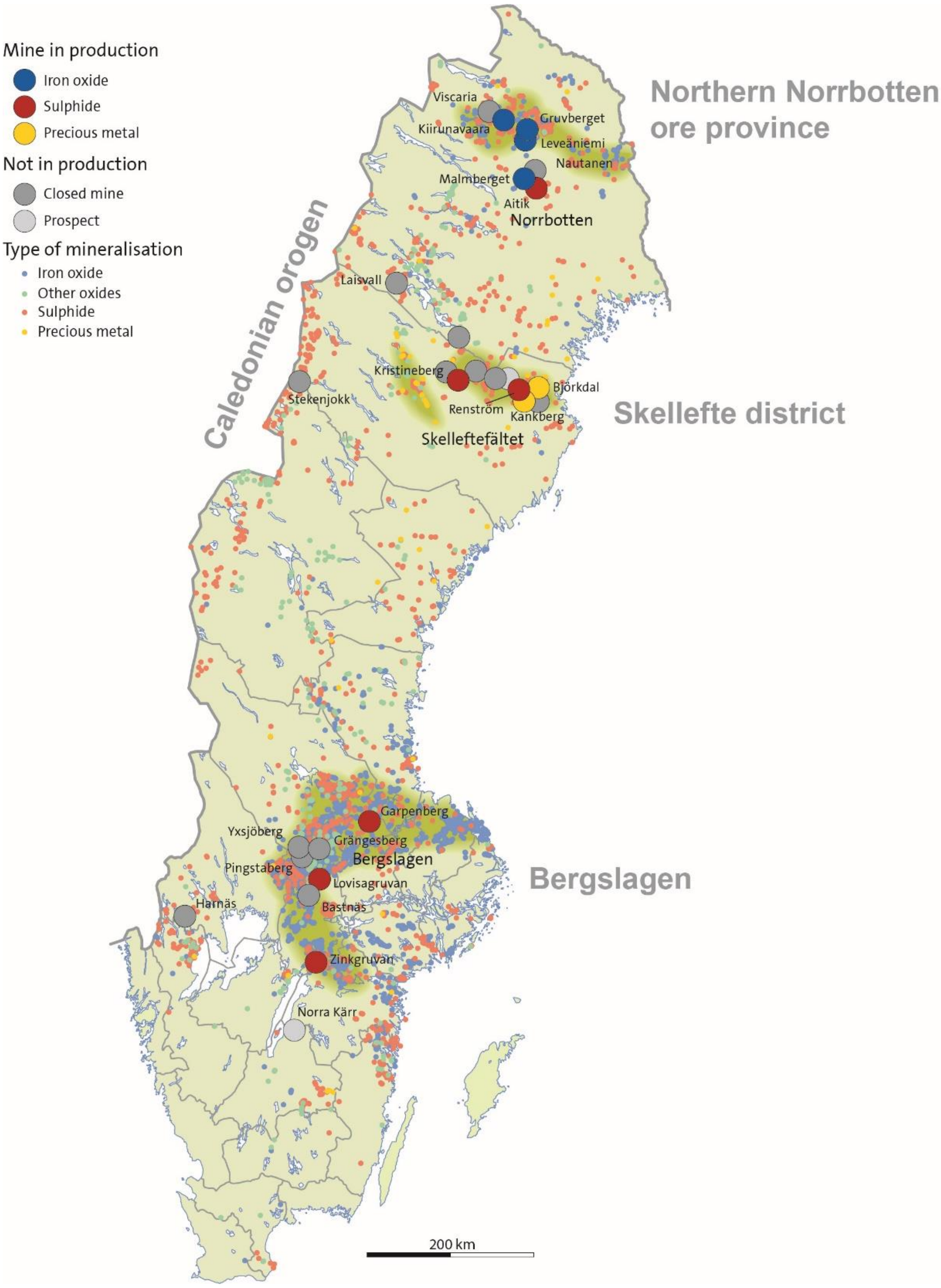

Figure 56: Mines and mineralisations in Sweden, state of activity from 2017. The currently active, major ore provinces of Northern Norrbotten, Skellefte district and Bergslagen are marked with dark green shading. (Source: SGU).

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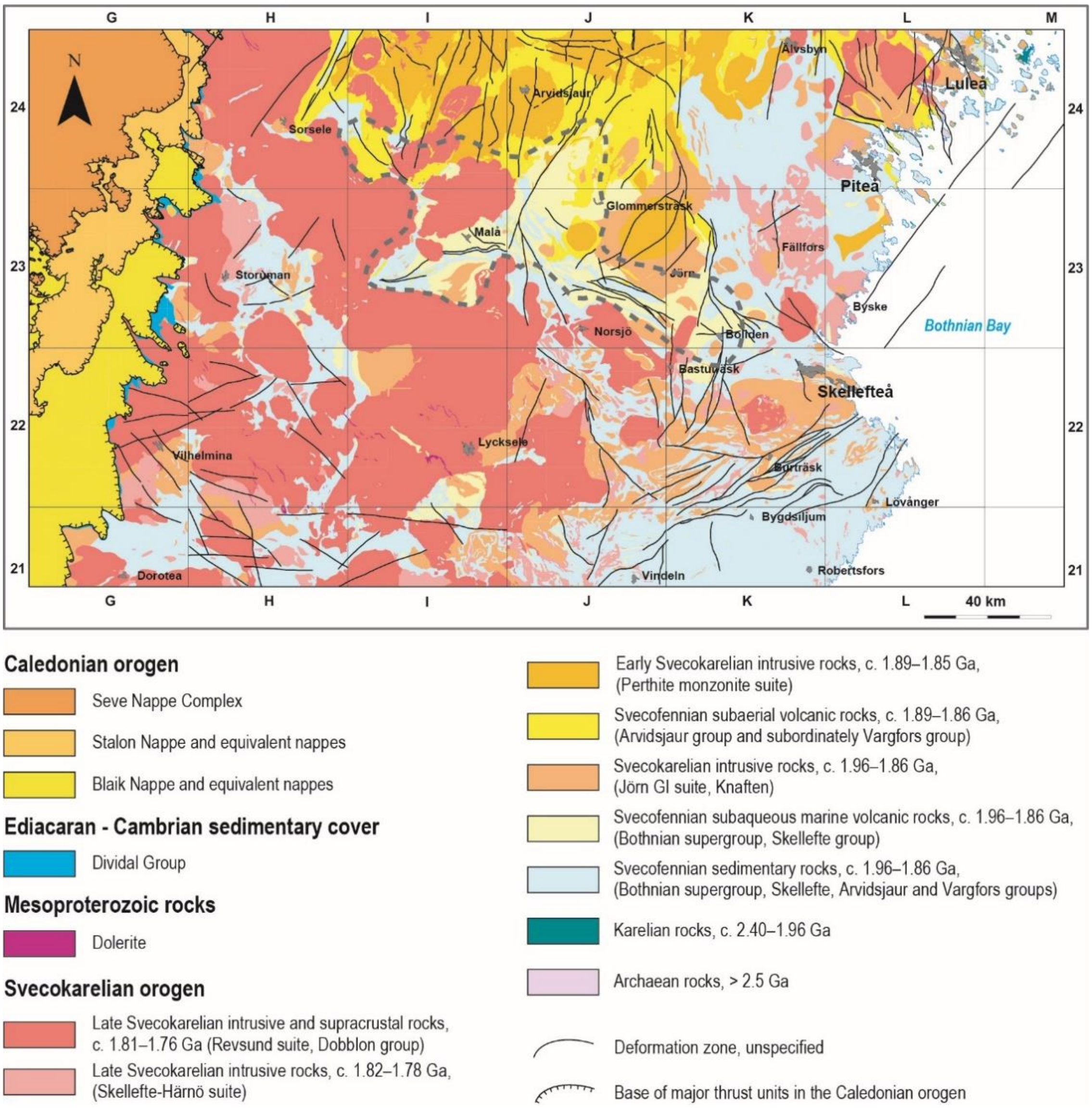

Figure 57: Simplified bedrock map of the Skellefte district and surrounding areas (Kathol and Weihed, 2005). The metallogenetic area of the Skellefte district is roughly outlined by a grey, dashed line (Hallberg, 2012). Reference grid is the former Swedish National Grid RT90, numbering refers to map sheets of the Swedish land survey.

The modern history of the Skellefte district began after World War I when the Kristineberg ore was discovered in 1918. At this time, exploration was carried out in the area by Centralgruppens Emmissionsbolag (predecessor to Boliden AB) and the Geological Survey of Sweden (SGU). The improvements made to electrical and electromagnetic geophysical exploration methods by Lundberg and Nathorst were a huge success and led to the discovery of several base metal sulphide ores in 1920–1922 in the central Skellefte district. In 1921 “Centralgruppens Emmissionsbolag” investigated an area where ore boulders had been found and trenches dug. They used the new electrical methods and found some interesting anomalies 2.5 km north of Bjurliden, misnamed Boliden on topographical maps. They decided to drill these anomalies and

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intersected auriferous arsenic-copper ore in December 1924. They had discovered the Boliden ore in the eastern Skellefte district. Because the name Boliden occurred on the topographical maps the name persisted and the Centralgruppens Emmissionsbolag became the Boliden Mining Company, now Boliden Mineral AB. Another discovery of auriferous base-metal ore was made during the 1920s in the central part of the district, but the Boliden ore was the only to be mined continuously until the Rävliden mine in the western Skellefte district opened in 1936.

With the major discovery of the Boliden ore, intensive mining activities were initiated in the Skellefte district. A concentrator was built at Boliden and a smelter at Rönnskär on the coast about 50 km east of Boliden. After a period of limited mining activities, a number of mining operations started in the late 1930s and during World War II such as Kristineberg (1940), Adak (1940), the nickel mine Lainijaur (1941) and others. A new concentrator was built in Kristineberg, and an approximately 100 km long cableway connected the two mining camps of Kristineberg and Boliden. Apart from the Boliden Company, SGU also undertook exploration in the Skellefte district. Economic prospects were handed over to the Boliden Company for development and mining.

The Boliden mine was closed in 1967, and the Adak camp (four mines) closed in 1976. New economic deposits in the eastern Skellefte district such as Renström, Långdal, Långsele and Kankberg were in production, with some interruptions between the 1950s and the late 1990s and compensated for the exhaustion of the older mines. In the central Skellefte district, Näsliden, Udden, Åsen and Kedträsk operated from the 1950s to the end of the century, also in that case with some interruptions.

In the 1980s, ore reserves in most of the existing mines were rapidly depleted and exhaustion was predicted within a decade for many mines. The Kristineberg concentrator was closed in 1991 partly because the Rävliden, Rävlidmyran, and Hornträskviken M mines in the western Skellefte district were exhausted. The ore from Kristineberg mine, which even today has considerable reserves, is currently trucked to the Boliden plant.

In the 1980s, the Boliden exploration strategy changed into more aggressive deep drilling within the ore-bearing sections of the district and regional programmes were directed towards gold. The gold exploration led to the discovery of gold ore at Åkerberg northeast of the eastern Skellefte district which was put into production in 1989. The deep drilling exploration resulted in two new discoveries during the late 1980s and the early 1990s: Petiknäs Norra and Petiknäs Södra only a few kilometres west of the Renström mine, and the Petiknäs Sädra mine was operated from 1989 to 2007.

In 1998 the exploration company NAN (North Atlantic Natural Resources) announced a new discovery at Storliden 8 km north of Malå in the western Skellefte district. The Storliden mine came into production in 2002 and operated until 2008.

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In the Maurliden deposit, known since the 1950s, the Maurliden Västra mine was opened in 2000 or 2002 and operated until 2018; the Maurliden Östra mine was active from 2010 to 2010.

State-run exploration by SGU, SGAB, NGS were carried out during the 1970s and the 1980s, but no economically viable deposits were found. However, this state-run exploration resulted in finding many sub economic mineralizations and prospects.

The state-run exploration ended in 1992; legislation was altered so that foreign exploration companies were able to commence exploration in Sweden. Swedish junior companies had been active for some time and discovered several VMS and precious metal deposits in the Skellefte district and the so-called gold line southwest of the Skellefte district. Some of these have been operated for a short time and, in the beginning of 2020, there are two active mines in the VMS deposits at Kristineberg and Renström and two in the precious metal deposits at Björkdal (gold) and Kankberg (gold and tellurium).

5.3. The Skellefte metallogenic area

The Skellefte metallogenic area is defined by the presence of different rocks hosting different type of mineralisations. The Skellefte Group hosts a large number of VMS, which form by far the most important economic deposit type in the mining history of the Skellefte district. The “Jörn” GI metagranitoids host non-economic porphyry copper deposits. Volcanic rocks of the Arvidsjaur Group and coeval intrusive rocks of the Perthite monzonite suite dominate the bedrock in the area north of the Skellefte district. Small copper mineralisations of the disseminated type are known to exist in these intrusive rocks, but all are so insignificant. The replacement copper- zinc (Cu±Zn) ores of the Adak mining camp, the Storliden mine, and the Svartliden mineralisation are all probably related to the early evolution of the volcanic arc. These deposits share several characteristics with VMS deposits but are characterized by stringer zone copper mineralisation instead of massive sulphide deposits. A few deposits, interpreted to have been formed by epithermal processes (i.e., the Boliden ore, Bergman Weihed et al. 1996), are known in the Skellefte district (epithermal gold). These deposits may have been formed under subaerial or shallow-water conditions.

5.4. Grade-Tonnage model of Skellefte VMS deposits

This model contains data from 46 selected volcanogenic massive sulphide (VMS) deposits within the Skellefte district (see deposit and occurrences in assessment sections). A spatial rule has been applied, according to which deposits less than 500 m from each other have been combined. In this model, all VMS representing the felsic volcanic massive sulphide type of deposits. Summary statistic for the VMS deposits are given in Table 19 and Figure 58.

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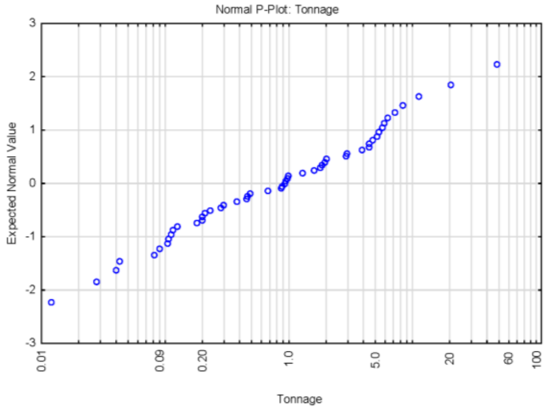
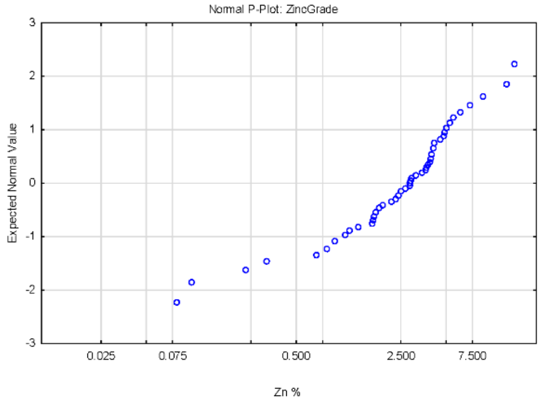
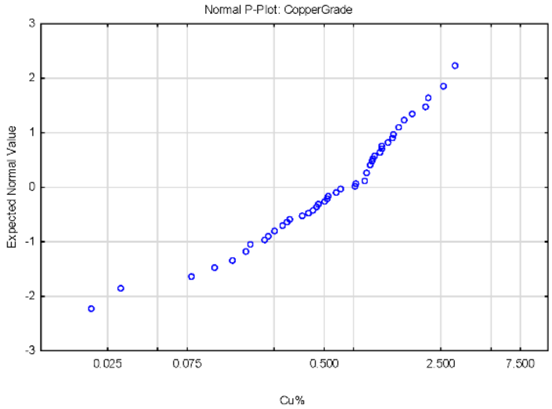
Table 19: Summary statistic for VMS deposits in Skellefte

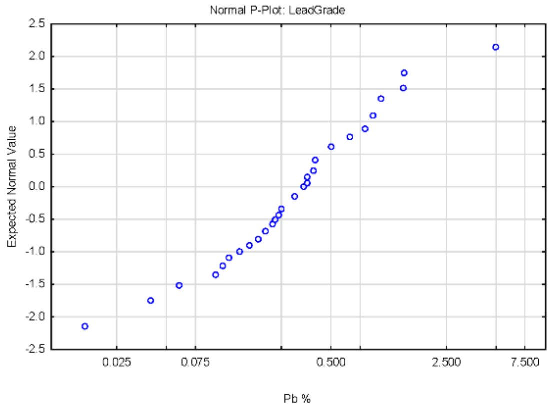
Variable	Descriptive Statistics (skellefte)						
	Mean	Minimum	Maximum	Percentile (10%)	Percentile (50%)	Percentile (90%)	Std.Dev.
Tonnage	3.434	0.012	48.560	0.090	0.935	7.209	7.391
CopperGrad	0.822	0.020	3.050	0.170	0.760	1.680	0.655
ZincGrade	3.237	0.000	14.300	0.320	2.870	5.600	2.774
LeadGrade	0.475	0.000	5.000	0.040	0.300	0.900	0.751
GoldGrade	1.477	0.060	15.500	0.275	0.640	3.090	2.589
SilverGrad	47.910	4.000	235.000	9.000	40.000	103.000	41.728

Mean: Arithmetic mean; St dev: Standard deviation; 90 %, 50 %, 10 %: Percentile values









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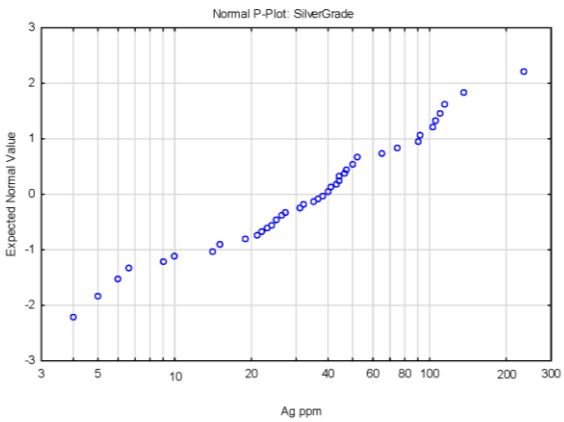

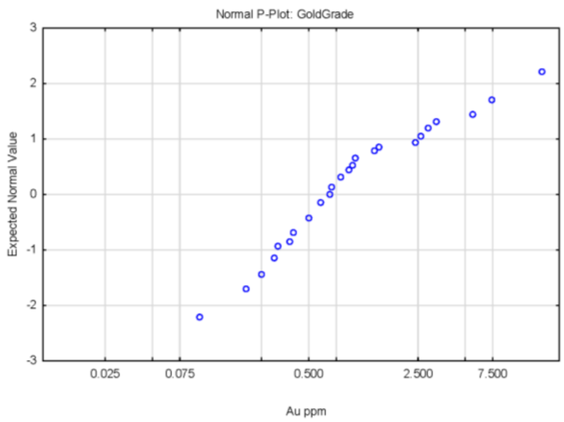

Figure 58: Normal probability plots of ore tonnage, copper, zinc, silver, lead and gold for felsic VMS deposits in Skellefte.

1. Grade summary

Summary comparison of the pdf (probability density functions) representing the grades and the actual grades in the grade and tonnage model for the felsic subclass of VMS deposits.

Pdf type: normal

Pdf is not truncated.

Number of discovered deposits in the grade and tonnage model: 46

Number of resources: 3

Quantiles (reported in percent)

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

	Component Cu		Component Zn		Component Ag		Component gangue	
	Gatm	Pdf	Gatm	Pdf	Gatm	Pdf	Gatm	Pdf
Minimum	0.020	0.00528	0.08	0.0131	0.00040	0.000704	87.2	18.5
0.25 quantile	0.325	0.28900	1.64	1.0800	0.00242	0.002	95.2	94.6
Median	0.695	0.55400	2.87	2.2000	0.00400	0.0035	96.8	96.8
0.75 quantile	1.060	1.06000	4.07	4.4100	0.00515	0.00609	97.7	98.1
Maximum	3.050	43.0000	12.60	81.4000	0.01360	0.0118	99.4	99.9

Compositional mean (reported in percent).		
	Gatm	Pdf
Cu	0.56200	0.56200
Zn	2.20000	2.20000
Ag	0.00354	0.00354
gangue	97.20000	97.20000

Composite variation matrix				
	Cu	Zn	Ag	gangue
Cu	0.00	2.480	1.810	0.913
Zn	2.490	0.00	0.521	1.140
Ag	1.820	0.521	0.00	0.720
gangue	0.915	1.140	0.722	0.00

Column Gatm refers to the actual grades from the grade and model; column Pdf refers to the pdf representing the grades.

The composite variation matrix has two parts: its upper triangle and its lower triangle. The upper triangle is the upper triangle of the variation matrix for the actual grades in the grade and tonnage model. The lower triangle is the lower triangle of the variation matrix for the pdf that the represents the grades. Thus, corresponding elements in the upper and lower triangles should be compared to one another.

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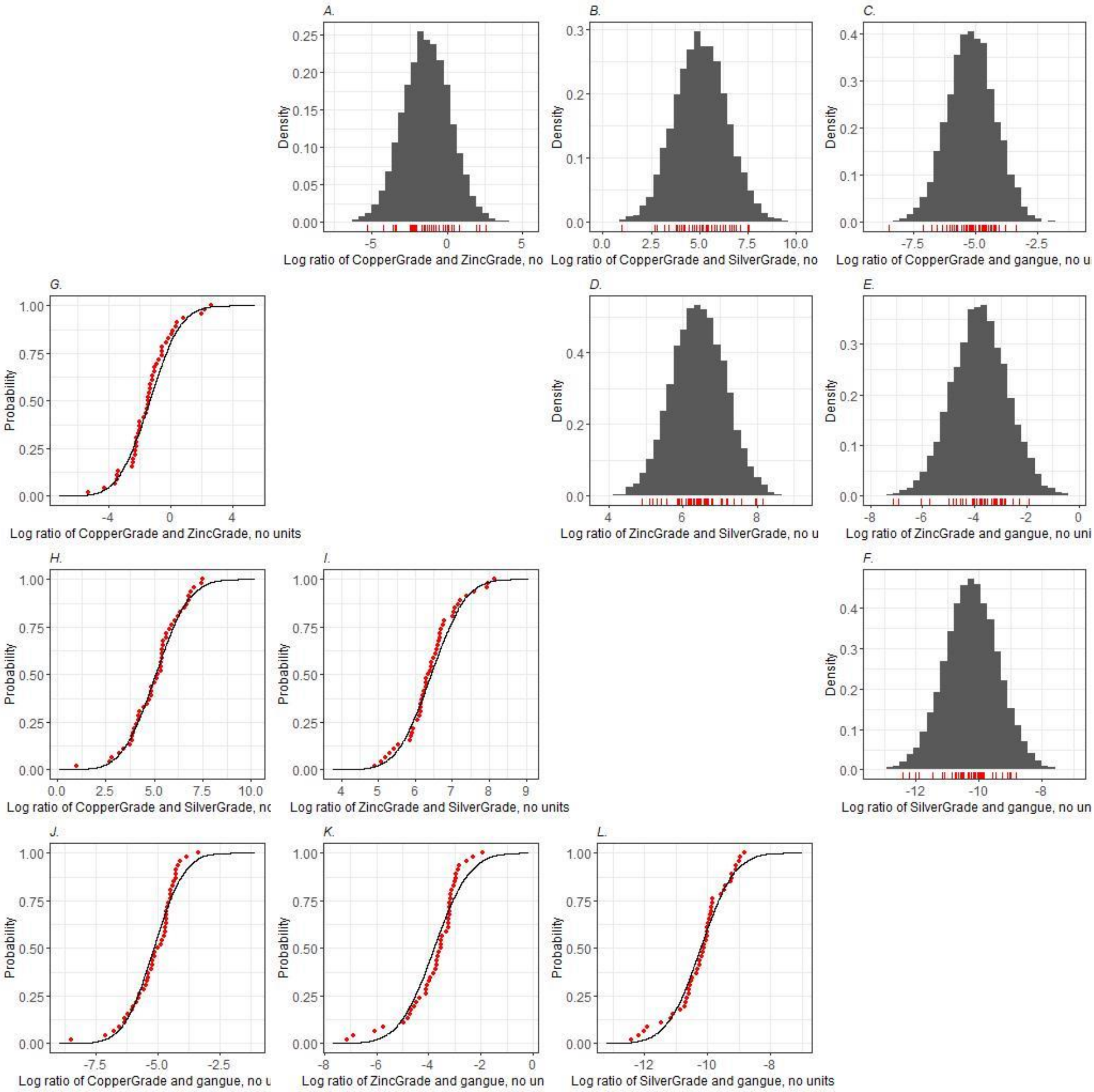

Figure 59: Plot of the estimated ore grade pdf in the Skellefte district.

2. Tonnage summary

Summary comparison of the pdf representing the tonnage and the actual tonnages in the model for VMS deposits of the felsic subclass.

Pdf type: normal
Pdf is not truncated.
Number of discovered deposits in the model: 46
Deviance = -14.3893

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The left table pertains to the log-transformed tonnages. Column Gatm refers to the actual tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.
The right table pertains to the (untransformed) tonnages. Column Gatm refers to the tonnages in the grade and tonnage model; column Pdf refers to the pdf representing the tonnages.

	Gatm	Pdf
Minimum	10.70	5.46
0.25 quantile	12.40	12.70
Median	13.80	13.90
0.75 quantile	15.30	15.00
Maximum	17.70	21.90
Mean	13.90	13.90
St. deviation	1.72	1.72

	Gatm	Pdf
Minimum	43000	234
0.25 quantile	243000	332000
Median	963000	1060000
0.75 quantile	44800000	3400000
Maximum	48600000	3230000000
Mean	3930000	4690000
St. deviation	8090000	19400000

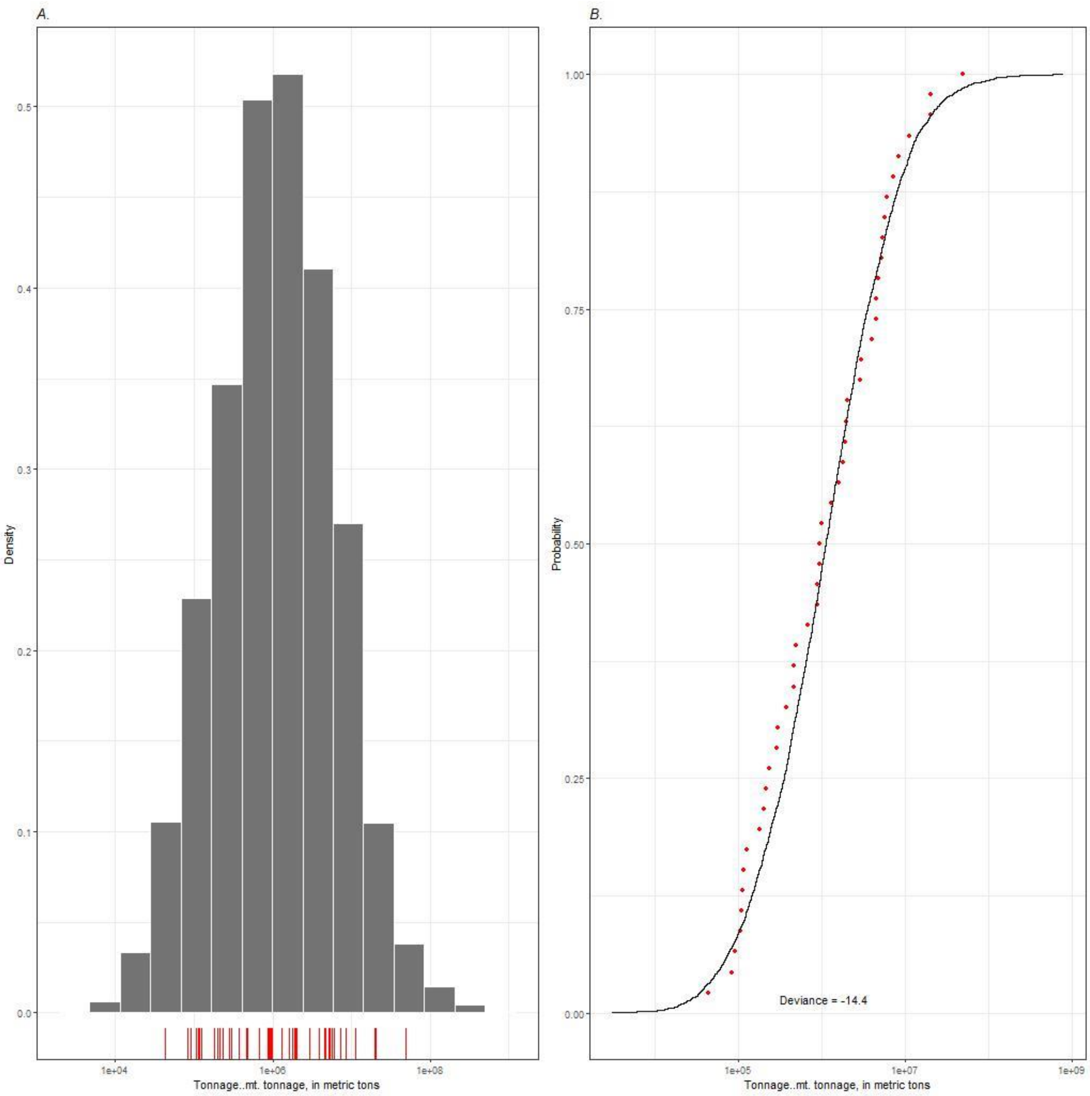

Figure 60: Plot of the estimated ore tonnage pdf in the Skellefte district.

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5.5. Descriptive model of Skellefte VMS deposits

The Skellefte district a loosely defined area of ca. 150 km by 80 km in northern Sweden, is part of a geologically permissive terrane for the existence of several types of metalliferous mineral deposits. It is one of the VMS districts not only in Sweden but also in the Fennoscandian shield. The Skellefte district is well-explored for volcanogenic massive sulphide deposits but the results of the study suggest that there are still substantial undiscovered endowments for such type of deposits. Geological-structural and geophysical data and model in the Skellefte district were presented by several researchers (c.f. Bauer et al., (2013; 2014 2015) ; Skyttä et al., 2012; Tavakoli et al., 2016)

Deposit examples
Kristineberg, Boliden, Renström (Kathol & Weihed 2005)
Rakkejaur (Trepka-Bloch 1989)

Geological environment

Host rocks
The Skellefte Group, which has an extremely variable internal stratigraphy, is composed predominantly of dacitic to rhyolitic volcanics with intercalations of andesitic to basaltic volcanics in the upper portions of the volcanic pile. in general, VMS deposits in Skellefte hosted mostly by felsic volcanic rocks in the upper parts of the Skellefte Group.

Mineralisation Environment
Volcanic arc formed in extensional, continental, environment. The transition from the Skellefte Group to the metasedimentary Vargfors Group correlated with the end of the above arc volcanism and differential uplift and subsidence of the arc.

Tectonic Setting
The Skellefte district has generally been regarded as a volcanic arc formed in Svecofennian times in a transition zone between an Archean continental landmass to the north and a Proterozoic sedimentary basin(Bothnian Basin) to the south (cf. Hietanen, 1975; Rickard and Zweifel, 1975; Adamek and Wilson,1979; Lundberg, 1980; Zweifel, 1982; Wilson et al., 1985, 1987; Lundqvist, 1987; Weihed et al.,1992; Öhlander et al., 1993; Gohl and Pedersen, 1994; Allen et al., 1996; Billström and Weihed,1996; Nitronen, 1997). It is now considered to be a remnant of a strongly extensionalPalaeoproterozoic intra-arc region that developed on continental or mature arc crust above a northerly dipping subduction zone and subsequently accreted to the Archean continent after 1.87 Ga.

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Deposit description

Mineralogy

The mineralization is dominated by sphalerite with lesser galena, pyrite, pyrrhotite as well as rare chalcopyrite and arsenopyrite. The host rock varies from tremolite skarn, dolomitic marble, graphitic shale and hydrothermally altered rhyolite including chlorite schist.

Texture/Structure

The ores are semi-massive to massive, as well as stringer-type mineralisations. WNW trends of spatial distribution of VMS deposits are plausibly due to regional-scale structural controls provided by shear zones with WNW trends. WNW trends of spatial distribution of VMS deposits are plausibly due to regional-scale lithostratigraphic controls provided mainly by the felsic volcanics which are mainly disposed along WNW-trending belt. Spatial distribution of VMS deposits and contact between the Skellefte and Vargfors groups support the timing of deposition which means most VMS deposit occur in the upper horizons of the Skellefte Group.

Ore Control

VMS deposits in the Skellefte district shows a strong correlation with the regional fault pattern resulting from upper crustal extension (D1).

Alteration

Alteration intensity from whole rock analysis; Na2O > 0.4% or Alteration index (Ishakawa).

Geophysical Signature

EM anomaly with coincidence gravity anomaly.

Geochemical Signature

Positive Cu, Zn anomalies in till.

5.6. Prospectivity mapping of the Skellefte district

For mapping of VMS prospectivity, thorough review of the geology and VMS mineralisation together with analyses of the spatial distribution of known VMS deposits and analyses of their spatial associations with different sets of geological features, geophysical and geochemical data, provide for conceptualization of spatial recognition criteria of VMS prospectivity (Carranza and Sadeghi 2010, Sadeghi et al., 2008). Integration of layers of evidence representing the spatial recognition criteria of VMS prospectivity based on mineral system approaches criteria (Table 20).

The analyses presented in this section aim to contribute a district scale answer to the question "Which parts of the Skellefte district are still prospective for VMS deposits?" based on empirical spatial associations of known VMS deposits (i.e., active/closed mines, prospects) with various factors of VMS prospectivity.

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From different spatial database of the Geological Survey of Sweden (SGU), we used the following datasets for district-scale mapping of VMS prospectivity in the Skellefte district:

- From the mineral resource database, FODD location and type of VMS deposit and their attribute (status, commodity, tonnage, grade, host rock, alteration etc.) extracted and completed within MAP project.
- A recent harmonized bedrock map, 1/50000. The bedrock reclassified in order to derive a map that is suitable for the prospectivity mapping. The structures reclassified according to the Azimuth similar to the process presented in Carranza and Sadeghi (2010).
- From geochemistry, the map of till geochemical data for Cu, Zn, and Pb and some major elements. The trace elements maps have been created from lithogeochemistry data base.
- From Geophysics, high resolution ground gravity data along road networks and airborne magnetic data with 200-m flight line spacing and 40 m altitude have been used. From these data sets, we created grid maps of Bouguer gravity and total magnetic intensity. Sadeghi (2008) describes the procedures applied to obtain these grid maps.

The following maps produced and used in the mineral prospectivity model based on spatial analysis and calculation of weights in mineral system approach for the VMS deposits in the Skellefte district (more details can be found in Carranza and Sadeghi, 2010 for calculation of weights). The results combined with the delineation of tracts section.

Table 20: Mappable ingredient of the VMS deposits in the Skellefte district based on mineral system approach applied for the mineral prospectivity

Mineral system approach (Mappable ingredients)	**Source**	Proximity to 1.89 rhyolites and basalt
	Transport	Proximity to area of high fault density
		NW-SE deformation zones
		Fault associated with low TMI
	Trap	Syn-volcanic lithologies with sediments
		Extrusive lithologies associated with TMI slope
	Deposition	Proximity to −22 to 353 nT TMI
		Rocks Bi> 1ppm
		till As≥ 41ppm
		Till Cu≥ 38 ppm
		Till Zn> ≥ 205 ppm

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5.7. Assessment for the western Skellefte district tract

Deposit type assessed

Deposit type: VMS
Descriptive model: VMS
Grade-Tonnage model: VMS Felsic

Location and Resource summary

The VMS deposits in the Kristineberg area in the western Skellefte district are hosted by the Skellefte Group of Palaeoproterozoic (1.9 Ga) greenschist to amphibolite facies, felsic to intermediate, submarine metavolcanic rocks (Allen et al. 1996; Årebäck et al. 2005). The Skellefte Group is overlain by the dominantly metasedimentary Vargfors Group, which consists of fine-grained turbiditic metagraywackes, graphitic phyllites, metaconglomerates and mafic-intermediate metavolcanic rocks and intrusions (Allen et al. 1996; Årebäck et al. 2005).

The western Skellefte district (Figure 61) is characterized by intense deformation of the metavolcanic rocks of the Skellefte Group and the sedimentary rocks of the Vargfors Group. The deformation intensity is partly a result of the original mica-rich rock, formed by large-scale alteration processes, and partly depending on the distance to the important deformation zones separating the bedrock of the Kristineberg area from less deformed rocks to the north-west and north. The Skellefte Group volcanic rocks form two antiformal structures or domes, where the core of the eastern, larger antiform is occupied by the 1907±13 Ma old (Bergström et al. 1999) Kristineberg metatonalite, belonging to the early Svecokarelian calc-alkaline granitoids, whereas the western antiform is cored by the late to post Svecokarelian Slappträsket pluton at approximately the same structural position. A synform with greywackes and intercalated ultramafic sills separates the two antiforms in the west.

The Skellefte Group metavolcanic rocks are mainly rhyolitic subvolcanic intrusions or lava domes and probably coherent volcaniclastic rocks. Willden (1986) suggested that the volcaniclastic rocks occupied longitudinal synvolcanic depressions or rifts, formed during extensional phases of Skellefte group volcanism. The depressions also focused later mafic volcanism, mainly emplaced as subvolcanic sills, and hydrothermal activity.

The sericite and chlorite alteration processes affected large volumes of rocks, where original textures can only very rarely be observed. To the south, higher grade metamorphism formed andalusite-cordierite-bearing assemblages in analogous rocks. Magnetite is another important alteration mineral and alteration zones are generally outlined by their magnetic patterns.

The north-western part of the Skellefte district is characterized by andesites and basalts of the Vargfors group, which outcrop around the late to post Svecokarelian Adak pluton. A number of

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mineralisations are known from this area: Halträsk (Allen et al. 1996), the Adak ores, and later discovered Storliden deposit.

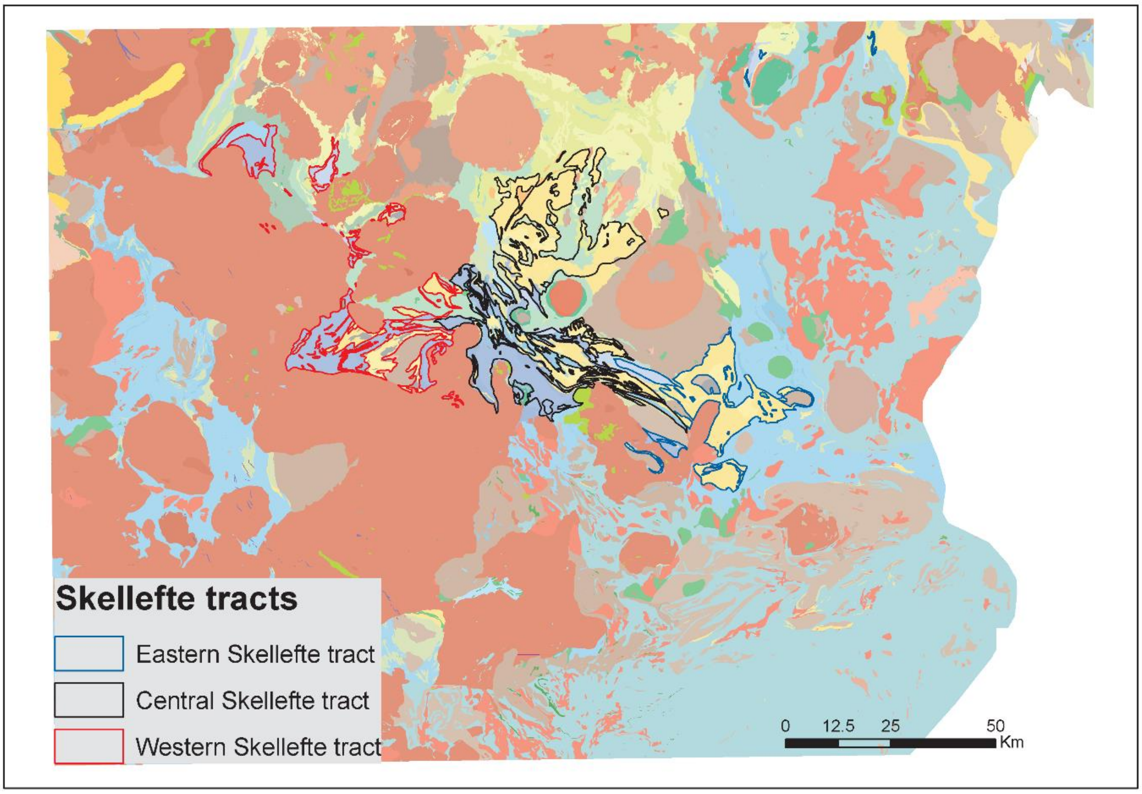

Figure 61: Simplified bedrock map of the Skellefte district shows tracts and surrounding areas. (Source of map: SGUs bedrock map database)

Delineation of the permissive tract

Geological criteria

Massive sulphide deposits occur in this area in two different stratigraphic settings. One type occurs near the top of the Skellefte Group, close to, or at, the contact with the overlying Vargfors Group (i.e., the Rävliden, Rävlidmyran, and Hornträsk orebodies), while the other type occurs lower in stratigraphy within the Skellefte Group (i.e., the various Kristineberg orebodies, and the Kimheden ore body). The orebodies from each of these stratigraphic settings have distinct characteristics in terms of size, composition, host lithologies, and alteration minerals present (Allen et al. 1996; Årebäck et al. 2005).

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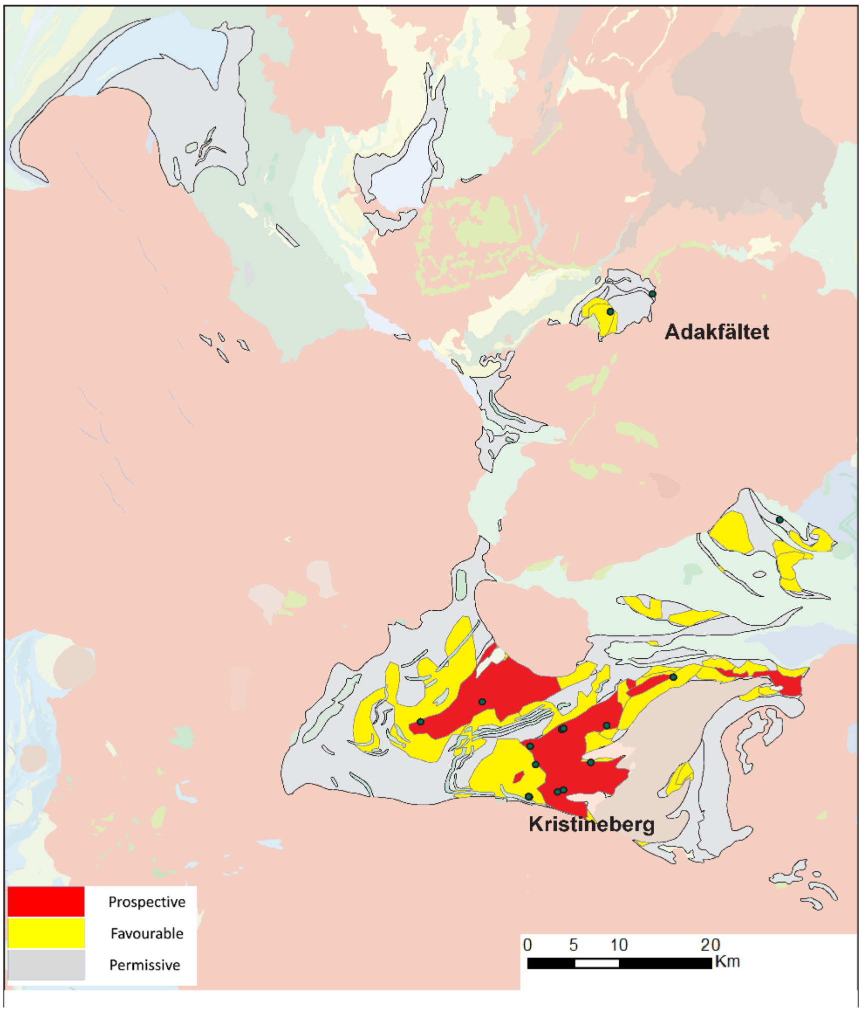

Figure 62: Map shows the prospective and favourable area resulted from prospectivity mapping in the Western Skellefte district tract. Sources: SGU bedrock database, Known mineralisations from SGU ore database.

In general, the deposits occurring in the lower stratigraphic levels (e.g., Kristineberg) are dominated by sphalerite, pyrite and chalcopyrite with lesser galena and Ag-rich sulphosalts and contain local zones of Au enrichment (Årebäck et al. 2005). They are hosted by strongly altered rhyolitic rocks, which are now schistose and rich in chlorite, sericite and quartz, with metamorphic porphyroblasts of cordierite and andalusite. Zones of massive pyrite occur in various parts of the Kristineberg deposit and also at the Kimheden deposit.

In contrast, deposits in the upper stratigraphic levels of the Skellefte group are dominated by sphalerite and pyrrhotite with lesser pyrite, chalcopyrite, arsenopyrite and Ag-rich sulphosalts; they are hosted by rocks rich in tremolite, talc, chlorite and dolomite with lesser clinozoisite, and are commonly underlain by chalcopyrite–pyrrhotite-dominated stringer zones which are discordant relative to stratigraphy. The stringers are developed in intensely chloritized and/or silicified felsic volcanic rocks that are flanked by quartz-sericite schists.

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The Adak area (Figure 62) is situated in the north-westernmost part of the Skellefte district. It is a key stratigraphic area, because the three major stratigraphic units – the Skellefte, Vargfors and Arvidsjaur groups – meet within a reasonably small area and their relationships can be studied. Hydrothermally altered, metamorphosed and deformed volcanic rocks of the Skellefte Group are exposed in the Adak dome structure, which is surrounded by younger sedimentary and volcanic rocks. All rocks of the dome structure show gentle dips away from the core of the dome. The oldest rock unit, exposed on Lappliden hill, is situated in the core of the dome. It consists of grey, fine-grained, quartz-muscovite-biotite-cordierite-plagioclase- bearing dacitic and rhyolitic metavolcanics rocks which have been exposed to large-scale alteration processes and subsequent medium grade metamorphism. in addition to the references above more details can be found in Årebäck et al. (2005); Barrett et al. (2005); Chevalier 1999; Skyttä et al. 2010, 2011,2013).

Deposits and prospects in the Western Skellefte district tract

There are several known deposits within this tract, of which one of them with high tonnage is Kristineberg deposit (Table 21). This deposit mined in 1935-1937 and from 1939 is still active mine. The Kristineberg mine has produced 31,7 Mt, from more than ten lenses since 1941, at an average grade of 3.74 % Zn, 1.04 % Cu, 0.24 % Pb, 1.4 g/t Au and 39 g/t Ag (Jansson et al. 2013).

Table 21: Deposit data for the Western Skellefte district tract.

Name	N(Sw)	E(Sw)	Discover	Start	Mt	Cu	Zn	Pb	Au	Ag	Prod.
Kimheden	7223053	668941	1959	1968	0.985	1.11	0.08		0.4	6	0.13
Mörkliden III	7218006	665186	1970	0	0.082	0.88	0.1	<0.1	0.6	5	
Mörkliden II	7217608	663032	1970	0	0.043	0.94	0.9	<0.1	0.3	40	
Granlunda	7224861	659450	1927	1943	0.125	0.76	1.3	0.9		15	0.003
Rudtjebäcken	7255932	672445	0	1947	4.743	0.9	2.9	0.1	0.3	10	4.74
Rävlidmyran	7221479	663112	1938	1953	7.209	0.98	3.7	0.4	0.9	47	1.90
Hornträskviken west II	7222759	665506	1948	0	0.107	0.5	3.8	1	0.3	75	
Kristineberg	7220238	667727	1918	1937	48.56	0.9	3.93	0.356	0.7	44	31.70
Rävliden	7220084	663530	1933	1936	1.936	0.9	4.1	0.8	0.4	90	7.54
Mörkliden I	7217638	662981	1944	0	0.21	0.02	4.1	0.4	0.3	75	
Hornträskviken W&C	7222831	665655	1948	1987	0.88	1.08	4.6	0.5	0.6	65	
Nyborg	7226742	674018	1943	0	0.296	0.53	4.8	0.5	0.2	41	
Mörkliden IV	7218152	665644	1970	0	0.115	0.17	4.9	0.4	0.1	25	
Storliden	7238719	682139	1998	2002	1.865	3.05	8.81	0.12	0.5	31	1.70
Vindelgransele	7223336	654750	1924	0	0.012	0	14.3	5	1	235	
Adakfältet	7254591	669218	1930	1932	6.3	2.02	0		0.6	9	6.34

Sw – SweRef, Discover- discovery year, Start- Startup of mining, Prod. – tonnage produced (Mt).

The Kristineberg area also includes several smaller past-producing mines including Rävlidmyran (7.18 Mt, mined 1950–1991), Rävliden (1.56 Mt, mined 1941–1988), Kimheden (0.13 Mt, mined 1967–1969 and 1974–1975) and Hornträskviken (0.64 Mt, mined 1981–1991) (Jansson et al. 2013). The entire Kristineberg area is still of considerable interest for mineral exploration.

In Adak field several sulphide occurrences, including the massive pyrite-dominated zinc-copper sulphide ore Rudtjebacken and the copper breccia and dissemination ores Adak, Brannmyran, and Lindskold are situated in the upper part of this altered unit. The ores are hosted in zones with

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stronger chlorite-antophyllite-skarn alteration. Minor occurrences of dark grey mudstones are found as intercalations in the uppermost parts of the unit.

In addition to the deposits mentioned above, there are additional 21 prospects and occurrences, which have been characterized as felsic VMS in this tract (Table 22).

Table 22: Data for prospects and occurrences in the Western Skellefte district tract.

Name	N_SWEREF	E_SWEREF	Tonnage	Cu%	Zn%	Pb%	Au ppm	Ag ppm	Comments
Aspliden	7221727	674757	-						
Brattmyrhögen	7226731	682942	-		5.5	0.9			
Brattmyrhögen Norra	7224850	684415	-						
Hornträskviken Östra	7223075	665991	-						
Hornträskviken mellersta	7222831	665655	0.88	1.2	2.3	0.3	0.6	50	S: 9,3 %
Hornträskviken Västra	7222637	665312	0.11	0.8	10.1	0.8	0.7	100	S: 12,8 %
Långträskåsen	7225810	658608	-	0.5	0.4	0.25		22	
Malådalen	7245506	661696	-						
Nåda	7227142	678226	-						
Nagruvan	7225421	660029	-						
Njasacken	7228636	667670	-						
Salmon Linders malm	7225856	664556	-	0.5					
Storliden	7238719	682139	1.16	4	10		0.3	30	
Sturemalmen	7221678	663060	-						
Svanaberg	7215168	670042	-						
Viterliden	7220778	670900	-						
Brännmyran	7253999	671045	0.98	1.7					
Karlsson Östra	7255039	669912	14	4.5					
Karlsson Södra	7254240	669972	-						
Lappliden	7255581	671625	-						
Lindsköld	7254885	669584	3.39	1.7					

Exploration history

Mineralisation at Kristineberg was first identified by means of electromagnetic investigations conducted by Hans Lundberg in 1918 (De Rietz 1951). After continued geophysical investigations and diamond drilling an underground investigation through a test shaft was done in 1934. Ore production commenced in 1936 but the production ramped up in 1940. In 1943 the cable way to the concentrator in Boliden was ready and the production was further increased. The mine in Kristineberg is still in production and today mining takes place below 1000-meter level.

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Estimation of the number of undiscovered deposits

The result of undiscovered deposit estimated based on MARK3 method are summarised in Table 23 and Figure 63.

Table 23: Summary of the pmf for the number of undiscovered deposits within the permissive tract.

Summary of pmf, number of undiscovered deposits	
Type	CustomMark3
Mean	5.27833
Variance	12.5909
St. Dev.	3.54836
Mode	2
Smallest N deposits in pmf	0
Largest N deposits in pmf	16
Information entropy	2.56038

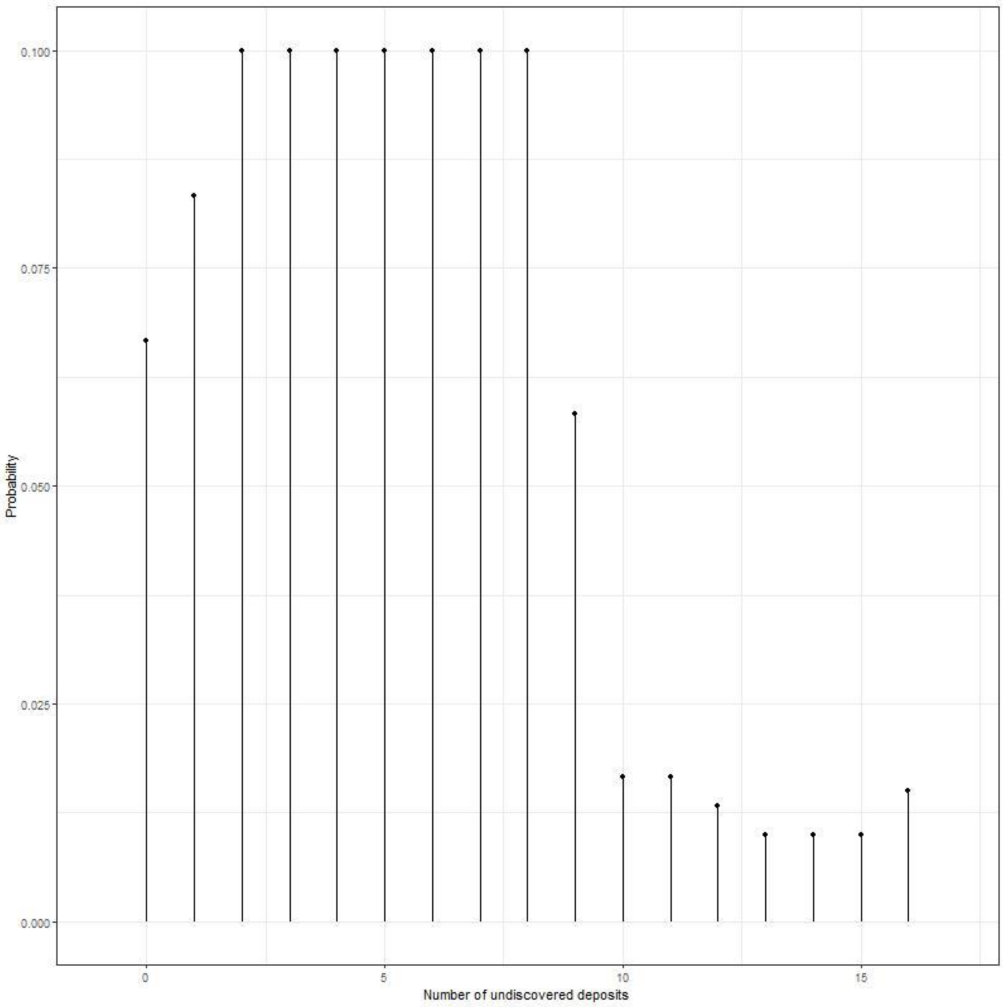

Figure 63: Plot of the estimated probability mass function (pmf) using the negative binomial option.

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Assessment of metal tonnages

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the VMS felsic grade-tonnage model using the MAP Wizard software. Results of the Monte Carlo simulation are presented as cumulative frequency plots (Figure 64) and selected simulation results are reported in Table 24. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralised rock.

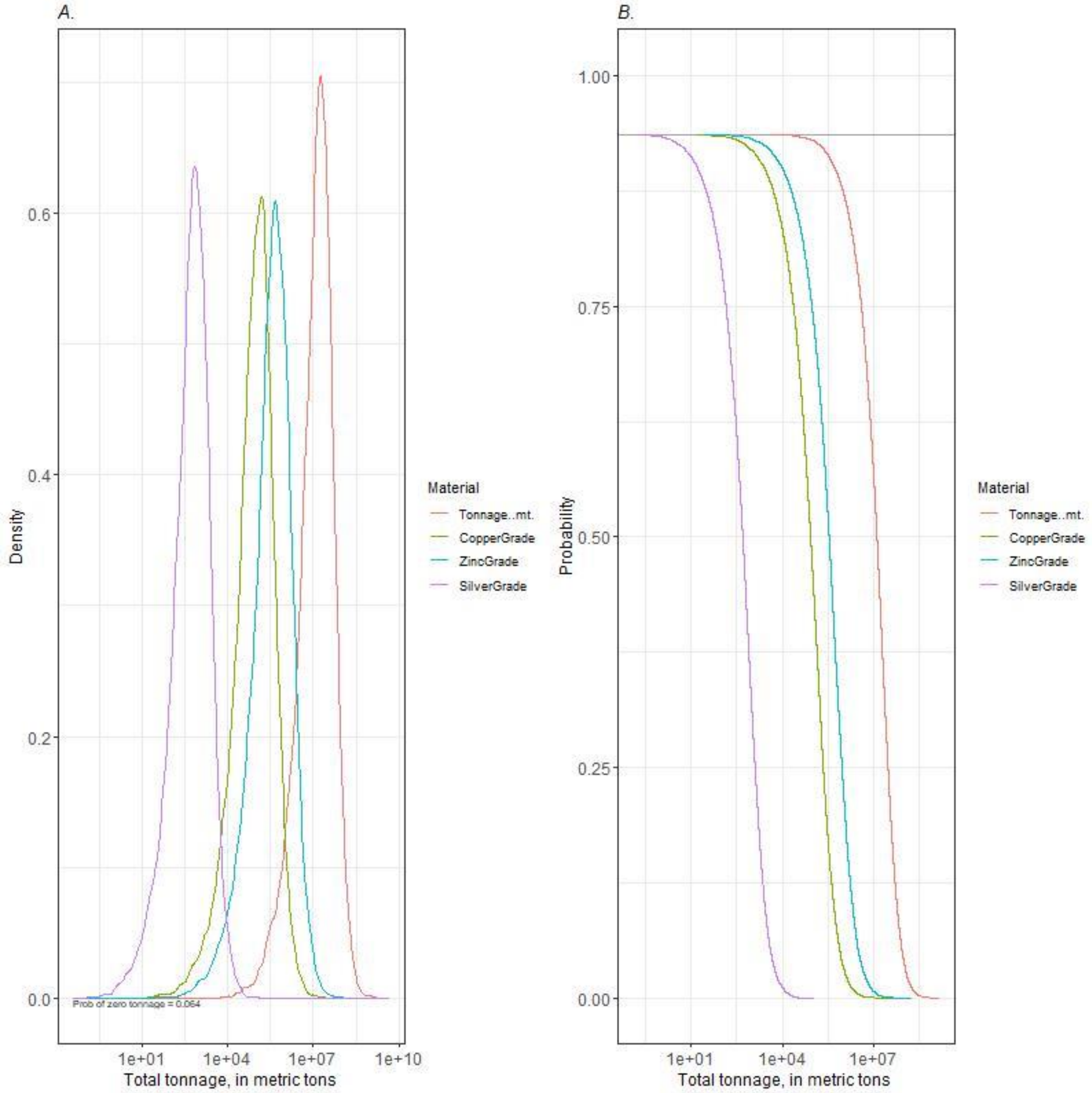

Figure 64: Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the western Skellefte permissive tract.

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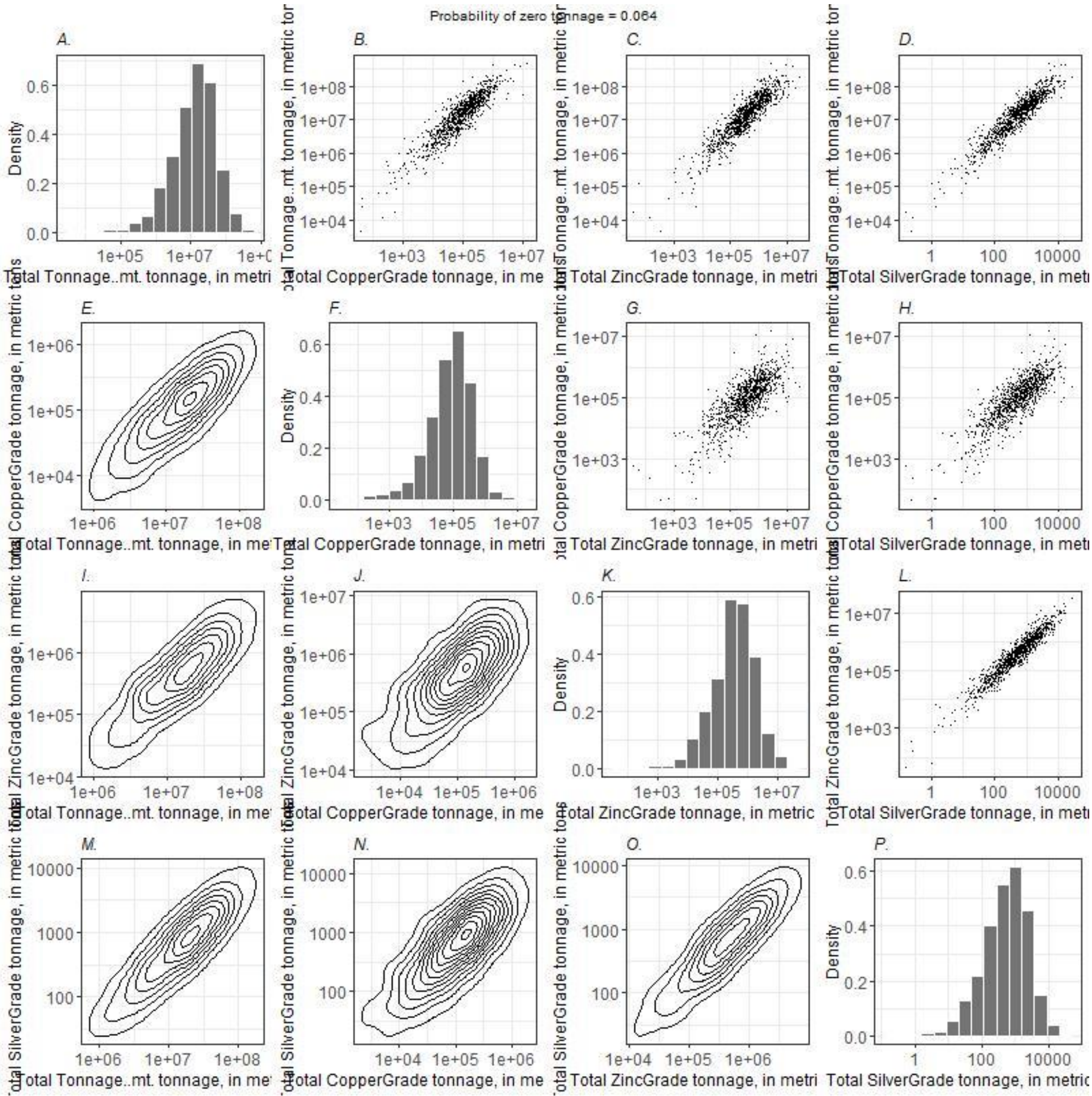

Figure 65: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

Table 24: Result of Monte Carlo simulations of undiscovered resources in the western Skellefte district tract.

Material	At least the indicated amount at the probability of							Mean	P (0)	P(>mean)
	Q_0.05	Q_0.1	Q_0.25	Q_0.5	Q_0.75	Q_0.9	Q_0.95			
Ore	0	532000.0	3920000	12700000	29100000	57300000	84200000	24400000	0.064	0.300
Cu (t)		2580.0	23300	84900	219000	487000	779000	222000	0.064	0.247
Zn (t)		9800.0	92900	342000	909000	2020000	3160000	884000	0.064	0.257
Ag (t)		16.5	144	508	1290	2660	4180	1180	0.064	0.272

Explanation

" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

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Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix				
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn	Ag
Ore	24400000	24700000	Ore	43000000	47500000	Ore	NA	0.624	0.685	0.772
Cu	222000	214000	Cu	976000	590000	Cu	0.667	NA	0.247	0.333
Zn	884000	893000	Zn	2510000	2800000	Zn	0.631	0.315	NA	0.823
Ag	1180	1200	Ag	2640	3120	Ag	0.752	0.438	0.729	NA

Explanation

1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.

2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

5.8. Assessment for the central Skellefte district tract

Deposit type assessed

Deposit type: VMS

Descriptive model: VMS

Grade-Tonnage model: VMS Felsic

Location and Resource summary

The central Skellefte district, comprises metavolcanic rocks south and west of the Jörn granitoid complex. The metavolcanic rocks of the central Skellefte district are bordered to the south by amphibolite grade metagreywackes of the Bothnian Supergroup, the Karsträsk intrusion of Jörn GI type and by felsic and mafic intrusions of the Revsund Suite. To the north the central Skellefte district is bordered by the Jörn granitoid complex and the Gallejaur intrusion. To the east it grades into the eastern Skellefte district whereas it narrows down to a short strip of mafic volcanic rocks in the west which is continuous into the western Skellefte district (Figure 61).

Delineation of the permissive tract

Geological criteria

In this area, Skellefte Group metavolcanic rocks of mainly rhyolitic composition occur in a number of antiformal structures, with Vargfors Group sedimentary rocks in narrow synforms in between (Figure 66). Graphite-and sulphide-bearing argillites form an important marker horizon between the groups. The rhyolites form coherent porphyritic subvolcanic intrusions or volcaniclastic mass flows. Breccias of varying origins are common (Allen et al. 1996). To the south, Vargfors Group sedimentary rocks dominate and to the north, the Gallejaur–Hognas intrusive complexes are exposed within the Vargfors Group volcanic and sedimentary rocks.

The western part of the central Skellefte district is intensely mineralized and several regional alteration zones exist with or without ores. Most alteration zones include weak quartz-sericite alteration with sulphide dissemination in porous volcaniclastic rocks. Carbonate alteration is

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common and may be mistaken for small occurrences of sedimentary carbonates in the ore-bearing stratigraphic horizons (Allen et al. 1996). Most alteration zones and ore deposits are restricted to the stratigraphic levels just below the above-named argillitic horizon. In addition to the references above more details can be found in Bauer et al. (2011); Bauer et al. (2013); Dehghannejad et al. (2012); Tavakoli et al. (2012) and Trepka-Bloch (1985).

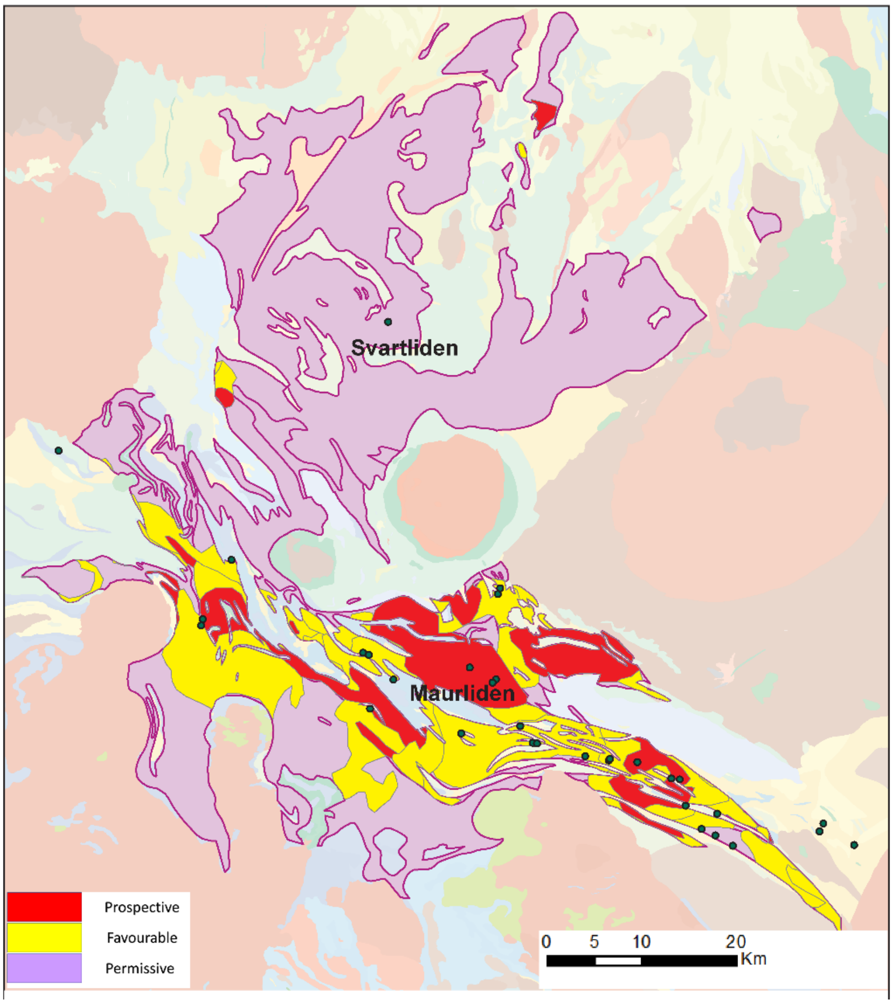

Figure 66: Map shows the prospective and favourable area resulted from prospectivity mapping in the central Skellefte district tract. Sources: SGU bedrock database, Known mineralisations from SGU ore database.

Deposits and prospects in the central Skellefte district tract

There are several known deposits within this tract, of which one of them with high tonnage is Rakkejaur and Eva deposits and several deposits have been mined (e.g. Rakkejuar, Udden, Maurliden, Näsliden, Holmtjärn, Högkulle, etc, see Table 25). The deposits in the Maurliden area (Maurliden Västra, Östra och Norra) are massive to disseminated base-metal sulfide deposits hosted by a porphyry rhyolite. Detailed investigations of the ore indicate that most of the mineralization took place as sub-sea replacement processes within the rhyolite.

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Table 25: Deposit data for the central Skellefte district tract.

Name	N(Sw)	E(Sw)	Discover	Mt	Cu	Zn	Pb	Au	Ag	Prod.
Svansele	7214579	727260	0	2.9	0.28	0.32	0.06	0.2	4	
Långviken	7221867	706800	1925	0.105	1.5	0.68	0.11	0.5	19	
Åsen east central	7209623	731803	1924	0.18	1.1	0.8	0.2	0.6	31	
Maurliden Norra	7221889	714352	1980	0.8682	0.14	1.06	0.16	0.7	27.3	
Maurliden östra	7221639	714102	1955	1.6	1.28	1.13		1	23	1.73
Åsen west central	7210381	730515	0	0.283792	0.96	1.63	0.24	0.9	44	
Näsliden Norra	7226307	692755	1922	0.94	0.59	1.65		0.8	25	
Bjurträsk södra	7215930	722664	0	0.0279	0.03	1.69	0	0	0	
Elvaberget	7219715	705078	0	0.93	0.46	1.69	0.18	0.5	22	
Åsen west	7210848	729488	0	0.23	0.9	1.9	0.3	0.4	40	0.29
Sjömalmen inre	7223703	704977	1924	2	0.45	2.17		0.5	35	
Bjurträsk norra	7216021	722752	1923	0.377	0.59	2.3	0.016	0.25	6.6	
Rakkejaur	7230683	694889	1921	17	0.3	2.4	0.2	1	50	0.71
Svartliden	7248228	706413	0	5.2	0.25	2.4	0.36	0.96	38	
Norrliden Norra	7218429	716144	1960	2.9523	0.77	2.5	0.25	0.38	43	
Maurliden Västra	7222762	712428	1957	5.687	0.23	2.67	0.25	0.68	44.2	3.98
Kedträsk	7211982	730643	1927	3.922781	0.31	2.86	0.22	0.4	21	0.69
Näsliden	7225855	692651	1952	4.48422	1.2	2.88	0.3	1.31	36.51	4.03
Bjurfors Mellersta	7217218	717058	0	0.483685	0.08	2.95	0.23	0.5	26.4	
Svansele Väggruva	7214507	727891	0	0.04	0.25	3.14				
Bjurliden	7216218	720920	0	0.676647	0.11	3.45	0.36	0.32	46.3	
Sjömalmen yttre	7223858	704575	1924	0.09	2.1	3.65		2.9	50	
Holmtjärn gamla	7228154	714489	1924	0.461	0.43	4	0.39	7.4	92	
Holmtjärn	7228586	714663	0	0.458939	0.4	4	0.4	7.4	92	0.46
Udden	7212563	728316	1955	5.95	0.37	4.18	0.34	0.7	32	5.95
Högkulla östra	7217910	711784	1932	0.112665	0.18	12.6	0.65	0.6	110	0.11
Bjurfors gruvfält	7217173	717369	0	0.2	2.6	0				0.29

In addition to the deposits mentioned above, there are additional 35 prospects and occurrences, which have been characterized as felsic VMS in this tract. They are listed in Table 26.

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Table 26: Data for prospects and occurrences in the central Skellefte district tract.

Name	N_SWEREF	E_SWEREF	Tonnage	Cu%	Zn%	Pb%	Au ppm	Ag ppm	Comments
Åliden	7222034	718346	-						S: 40 %
Åmliden	7218114	689301	-						
Åsen Östra	7208970	732761	-						
Åsen Östra mellersta	7209608	731853	0.29						
Åsen västra	7210848	729488	-						
Åsen västra mellersta	7210381	730515	-						
Arnberg	7203158	708289	-						
Österbäcken	7218326	718779	-						
Bastutjärn	7214003	697497	-						
Bjurfors Östra	7217172	717368	-	2.6			0.5		S: 27 %
Bjurfors Västra	7217463	716675	-						
Gävliden	7212550	699870	-						
Gissträsk	7214141	699245	-						
Grubbfallet	7235587	703075	-						
Högbränna	7247801	719916	-						
Heden	7208166	708925	-						
Holmtjärn	7221563	715256	-	0.01	0.69	0.08	0.1	7	S: 8 %
Inre Sjömalmen	7223595	705128	1.3	0.5	2.2	0.4	0.8	47	S: 32 %
Kedträskheden	7211698	727127	-						
Kvammarliden	7209063	700914	-						
Långviken	7221867	706800	0.1	1.5	0.68	0.11	0.5	19	S: 25,8 %
Lillholmsträsk	7216017	697326	-						
Lomviken	7222555	706681	-	0.78	2.52	0.06	0.4	12.7	S: 18,9 %
Mörtträsk Norra	7240765	702209	-						
Mörtträskheden	7239560	701025	-				1.1	5	
Näset	7217320	723446	-						
Näverliden	7256136	714960	-						
Näverliden	7216353	723718	-						
Norrliden Södra	7218162	715774	-	0		0	3	25	S: 18 %
Rågången	7222498	706152	-	1.4	0.4		0.7	18	S: 19 %
Rundklumpen	7223355	706671	-	0.08	1.6	0.1		17	S: 28,1 %
Rutselheden	7216396	720033	-						
Skäggträskberget	7217897	710937	-	2	7.8	0.8	1.6	112	
Storholmen	7230929	706334	-						
Svansele Selgruva	7214642	728289	-						
Svartliden	7248228	706413	0.47						
Tistelmyran Östra	7224372	711147	-						
Tistelmyran Norra	7225466	711453	-						
Tistelmyran Västra	7224666	709904	-						
Yttre Sjömalmen	7223858	704575	0.1	2.1	3.65	0.39	2.9	50	S: 33,8 %

Exploration history

After the discovery of massive sulfide ore in Kristineberg in 1918 and especially after the discovery of the Boliden deposit in 1924, an intensive exploration of the areas between these deposits started, with boulder tracking and electromagnetic methods (slingram at its precursors). Most of the deposits in the areas was identified during this long-lasting campaign.

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Estimation of the number of undiscovered deposits

The result of undiscovered deposit estimated based on MARK3 method are summarised in Table 27 and Figure 67.

Table 27: Summary of the pmf for the number of undiscovered deposits within the permissive tract.

Summary of pmf, number of undiscovered deposits	
Type	CustomMark3
Mean	6.795
Variance	17.9396
St. Dev.	4.23552
Mode	3
Smallest N deposits in pmf	0
Largest N deposits in pmf	18
Information entropy	2.75946

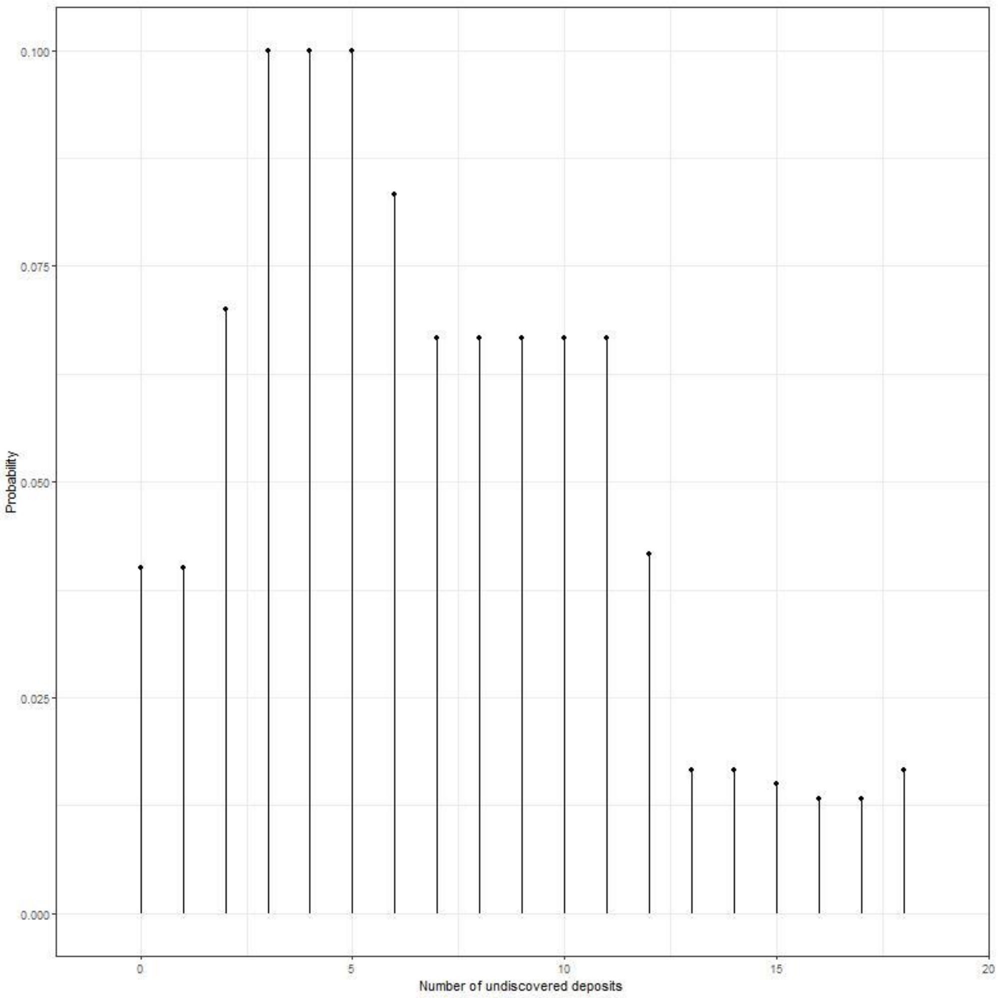

Figure 67: Plot of the estimated probability mass function (pmf) using the negative binomial option.

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Assessment of metal tonnages

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the VMS felsic grade-tonnage model using MAP Wizard software. Results of the Monte Carlo simulation are presented as cumulative frequency plots (Figure 68) and selected simulation results are reported in Table 28. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralised rock. Figure 69 shows plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

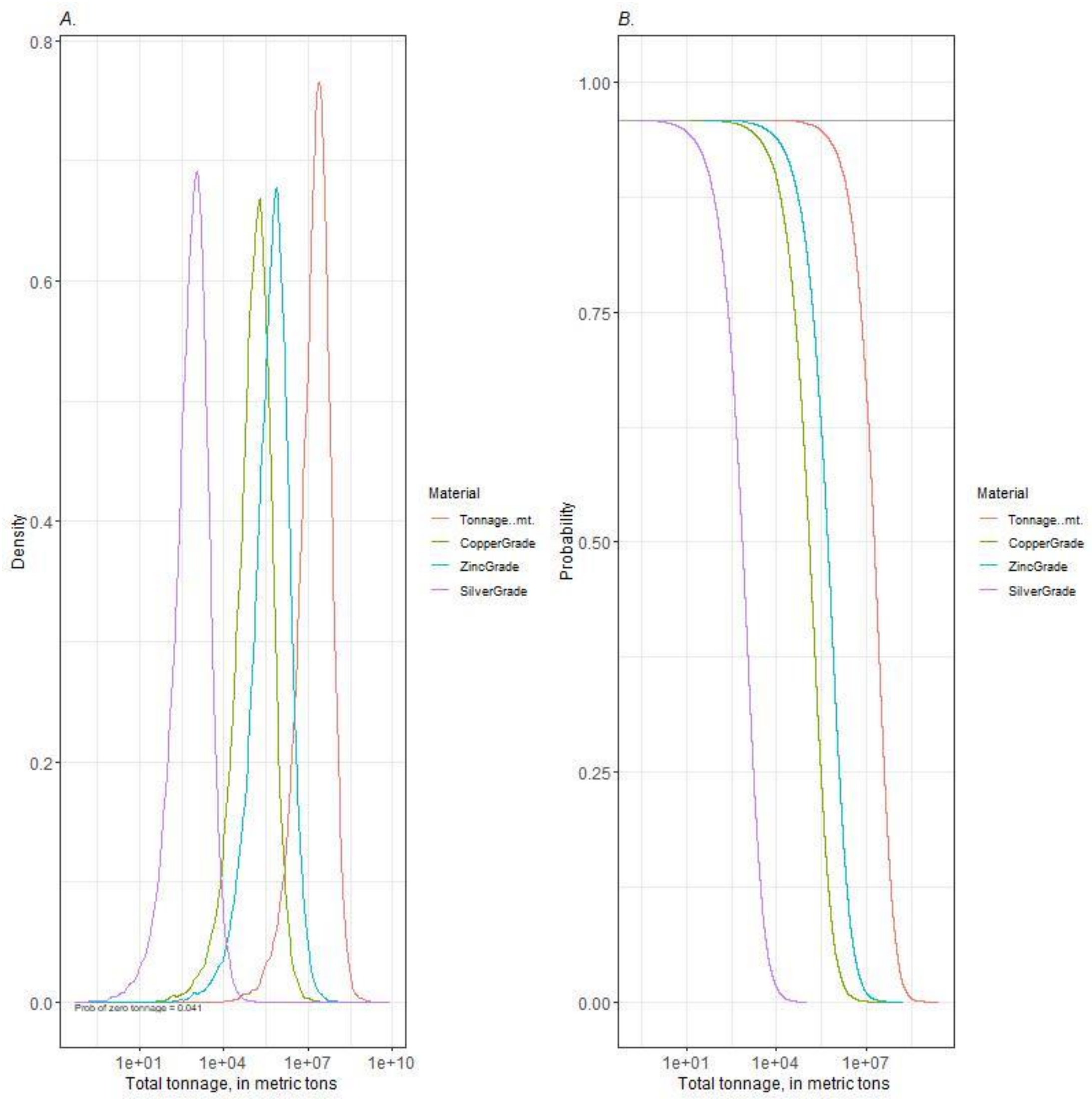

Figure 68: Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the central Skellefte permissive tract.

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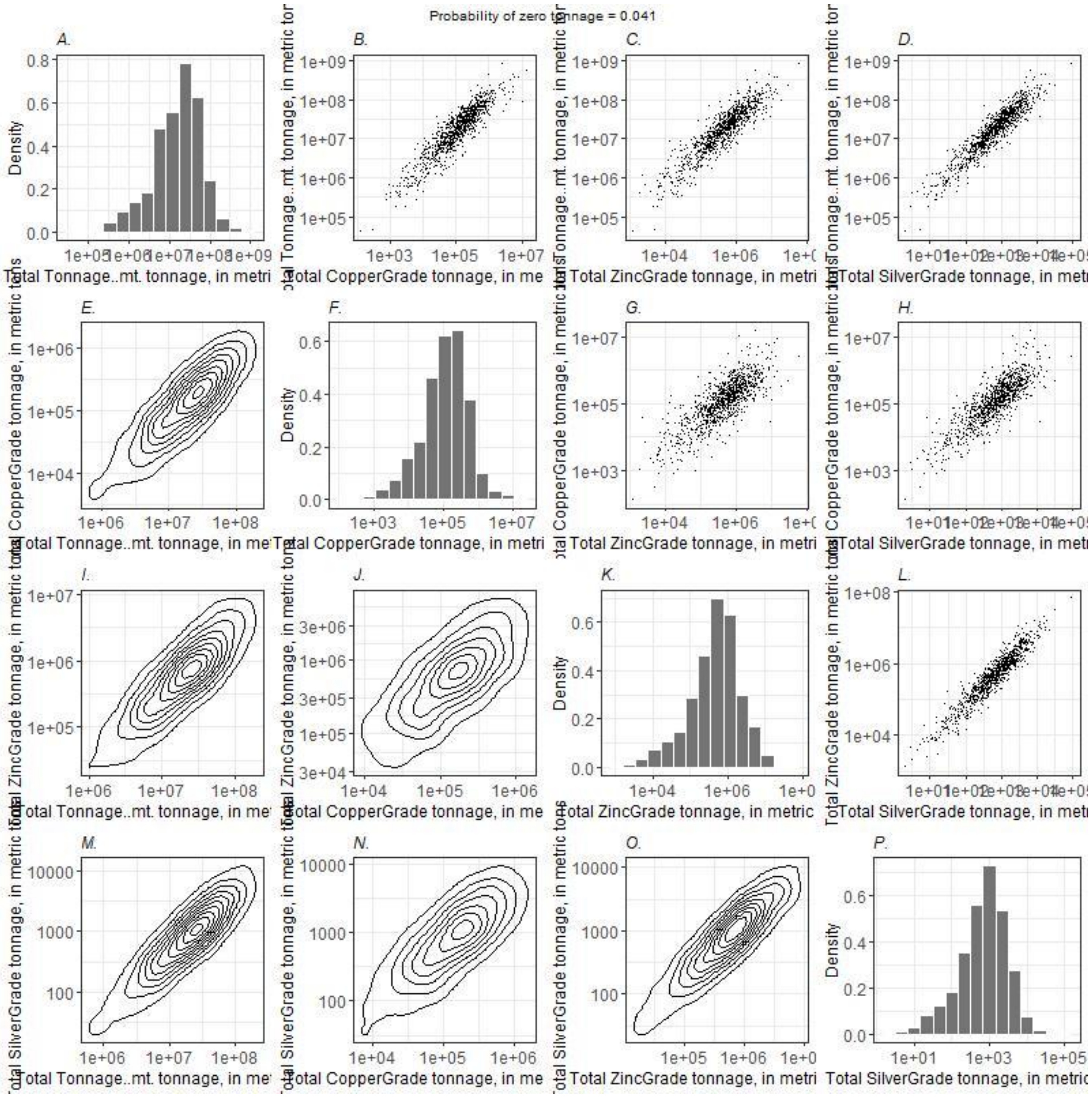

Figure 69: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

Table 28: Result of Monte Carlo simulations of undiscovered resources in the central Skellefte district tract.

Material	At least the indicated amount at the probability of							Mean	P (0)	P(>mean)
	Q_0.05	Q_0.1	Q_0.25	Q_0.5	Q_0.75	Q_0.9	Q_0.95			
Ore	2.43e+05	1.67e+06	6450000	17700000	38000000	72300000	1.05e+08	31400000	0.0412	0.311
Cu (t)	1.01e+03	9.17e+03	40100	122000	297000	613000	9.44e+05	280000	0.0412	0.266
Zn (t)	3.89e+03	3.45e+04	161000	503000	1210000	2530000	4.02e+06	1130000	0.0412	0.269
Ag (t)	6.83e+00	5.68e+01	246	726	1700	3410	5.22e+03	1510	0.0412	0.283

Explanation

" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

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Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix				
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn	Ag
Ore	31400000	31900000	Ore	52000000	54200000	Ore	NA	0.582	0.663	0.765
Cu	280000	275000	Cu	1010000	671000	Cu	0.670	NA	0.268	0.352
Zn	1130000	1150000	Zn	2730000	3190000	Zn	0.633	0.319	NA	0.821
Ag	1510	1550	Ag	3030	3550	Ag	0.754	0.442	0.730	NA

Explanation
1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.
2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

5.9. Assessment for the eastern Skellefte district tract

Deposit type assessed

Deposit type: VMS
Descriptive model: VMS
Grade-Tonnage model: VMS Felsic

Location and Resource summary

The eastern part of the Skellefte Group contains numerous important VMS deposits. The Skellefte Group here is stratigraphically overlain by metasedimentary rocks of the Bothnian Supergroup towards east. The structural trend changes from the normal Skellefte district west-northwest trends to north and north-east trending folds and fault structures within the metasedimentary rocks. VMS deposits are confined to the southern part of the Boliden domain, and the Skellefte Group rocks are almost devoid of mineralisation farther to the north (Figure 61).

Delineation of the permissive tract

The Boliden area in the eastern Skellefte district is built up of rocks belonging to the Skellefte and Bothnian groups which are folded into an anticline with a north-east–south-west striking axial trace. A coarse quartz-feldspar porphyritic, rhyodacitic subvolcanic rock from the core of the anticline was dated at 1884± 6 Ma (Billström & Weihed 1996), which is one of the oldest ages found so far among Skellefte Group rocks. The host rock of the Boliden ore is a feldspar porphyritic subvolcanic dacite at the stratigraphic top of the Skellefte Group, which was found to have an age of 1869±15 Ma with the Kober technique (Bergman Weihed et al. 1996). As this is the youngest age recorded so far for the Skellefte Group, the Boliden area seems to contain a rather complete stratigraphic section through the Skellefte Group.

On the limbs of the anticline, the Skellefte Group metavolcanic rocks are overlain by volcanic sandstones and sedimentary rocks belonging to the Bothnian Supergroup. The anticline is

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truncated towards the north-east by a north-west striking, probably ductile deformation zone and by a rather more brittle, north–south striking deformation zone in the west (Lundström & Antal 2000). The south-eastern part of the area has been metamorphosed to lower amphibolite facies whereas the remainder has been altered to greenschist facies.

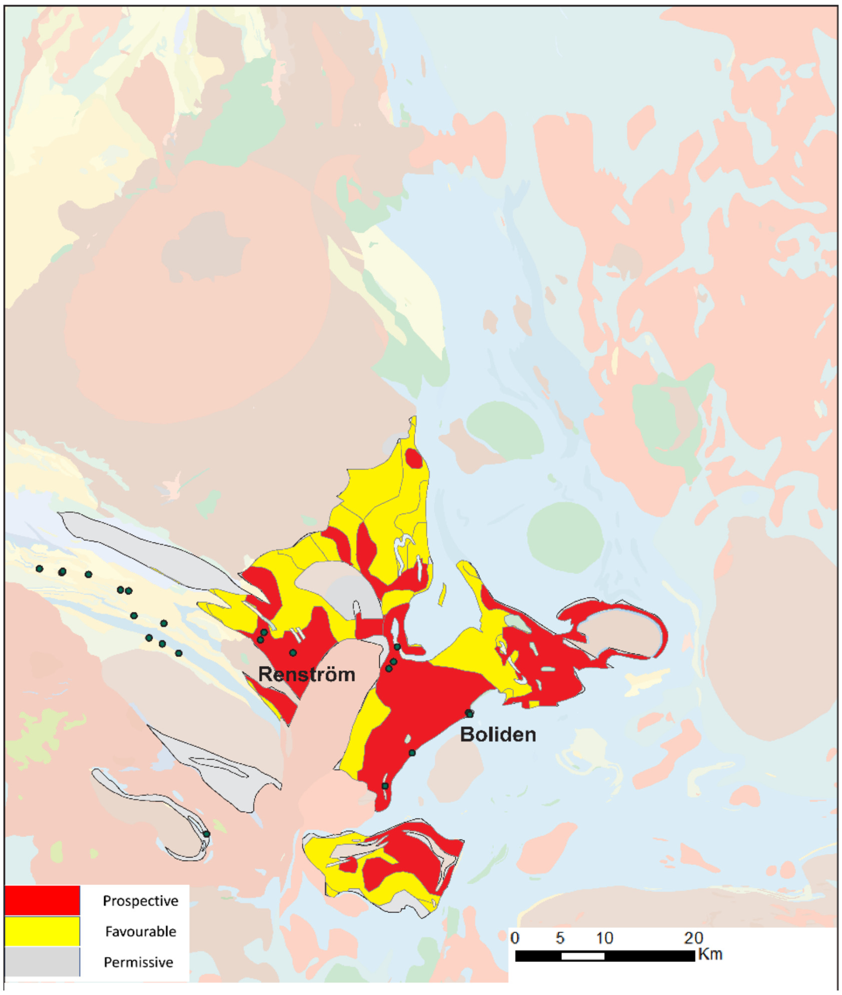

Figure 70: Map shows the prospective and favourable area resulted from prospectivity mapping in the eastern Skellefte district tract. Sources: SGU bedrock database, Known mineralisations from SGU ore database.

The lower part of the Skellefte Group in the Boliden domain consists of rhyolitic lavas, subvolcanic intrusions, and volcaniclastic rocks, whereas the upper part is composed of dacitic subvolcanic intrusions and volcaniclastic rocks. Some minor sedimentary intercalations occur locally between the two units. Small quartz porphyritic stocks intruded the dacites, for example in the footwall of the Boliden and Langsele deposits. Mafic volcanic rocks are found in the uppermost part of the Skellefte group, immediately below the argillites, indicating the transition into the metagreywackes of the Bothnian Supergroup. In the area north of the Kankberg deposit and east of the Boliden–Langsele–Langdal deposits, this transition zone is characterized by volcanic mass flows of rhyolitic and dacitic composition interbedded with mudstones and siltstones.

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The rocks of the Boliden domain show several types of alteration assemblages. Regional, weak quartz-sericite alterations are common in porous volcaniclastic rocks, whereas the lavas and subvolcanic intrusions are generally less altered. Close to the VMS deposits, there are more intense sericite–chlorite alteration zones. Rather intense quartz–sericite–pyrite alteration zones without any known associated ore deposit are occasionally encountered.

Characteristic of the Boliden area is a syn-metamorphic growth of actinolite, which occurs frequently and with varying intensity in all types of rocks. The high-grade Renström and Petiknäs ores are described as a separate domain between the Udden domain and a north-east to south-west trending late to post Svecokarelian granite intrusion of the Revsund Suite (Figure 70).

Deposits and prospects in the Eastern Skellefte district tract

The VMS deposits of the Boliden domain (Table 29) include the large pyrite ore body of Langsele, the sphalerite galena- rich Langdal ore (Talbot 1988, Assefa 1990, Weihed et al. 2002) and the copper-rich deposits of Åkulla Västra, Åkulla Östra, and Kankberg. A precious metal-rich ore zone occurs in the stratigraphic footwall to the massive ore of the Langdal deposit. High gold grades are common within the chalcopyrite-rich zones in Åkulla Östra and Kankberg.

Table 29: Deposit data for the eastern Skellefte district tract.

Name	N(Sw)	E(Sw)	Discover	Start	Mt	Cu	Zn	Pb	Au	Ag	Prod.
Åkulla East	7208970	748585	1921	1997	0.200211	1.68	0.23	0.04	3.28	14.1	
*Boliden	7204997	754459	1924	1926	8.388134	1.4	0.9	0.3	15.5	50	8.32 Mt
*Kankberg	7210140	748890	1937	1966	1.8	1.4	1.8	0.3	2.6	52	2.50 Mt
Långsele	7201841	750050	1926	1956	11.19	0.52	3.88	0.14	0.8	24	11.20 Mt
Petiknäs södra	7210689	738188	1988	1992	5.346996	0.9	5	0.9	2.4	106	5.40 Mt
Långdal	7199265	747933	1937	1950	4.48511	0.17	5.32	1.39	1.4	115	4.48 Mt
Petiknäs norra	7211262	738461	1986	0	1.3	1.3	5.6	0.9	5.6	103	
Renström	7209672	740736	1928	1948	20.24	0.63	7.26	1.364	2.6	136	13.69 Mt
Åkulla	7208435	748237	1932	1947	0.98	1	0		0.7		1.18 Mt

Sw – SweRef, Discover- discovery year, Start- Startup of mining, Prod. – tonnage produced (Mt).

(*) Boliden and Kankberg are possibly epithermal deposits)

In addition to the deposits mentioned above, there are additional 11 prospects, which have been characterized as felsic VMS in this tract. They are listed in Table 30.

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Table 30: Data for prospects and occurrences in the eastern Skellefte district tract.

Name	N (Sw)	E(Sw)	Comm-odity	Mode of occurrence	Host rock	Min.	Wall rock	Alteration
Bjurvattnet	7203685	749577	Cu;		felsic volc.			
Boliden Kyrkogårds-gruva	7205655	755051	Cu;	dissemination in host rock;	schist/gneiss	cpy		
Boliden södra	7204849	754561	Zn; Pb;	dissemination in host rock;	volc.	ga, po, sl	andesite; dacite; mudstone;	chlorite; muscovite;
Brännan	7206201	746945	Cu;	massive;	volc.	apy, cpy, py, po	metasediment ary rock; volcanic rock;	cordierite; muscovite; skarn; quartz;
Fjällboda	7218998	750681	Cu; Zn; Pb;	dissemination in host rock;	volc	cpy, ga, po, sl	volcanic rock;	
Kyrkvägs-malmen	7210193	740834	Pb; Zn; Cu; Au;	massive;	felsic volc.	cpy, ga, py, po, sl	volcanic rock;	chlorite; muscovite;
Rengård	7207332	737631	Cu; Zn; Pb;	vein; dissemination in host rock;	rhyolite	cpy, py, po		chlorite;
Renström Östra	7209510	741373	Pb; Zn; Cu; Au;	massive;	felsic volc.	cpy, ga, py, po, sl	volcanic rock;	chlorite; muscovite;
Stavträsk Östra	7209663	747900	Fe-sulphide s;	dissemination in host rock;	felsic volc.	py, po		
Storkågeträsk	7216231	753316	Fe-sulphide s;	massive; semimassive;	metased.	py, po		
Vikborg	7202458	739593	Cu;					

Exploration history

During the first decades of the 20th century, several small holding companies called "emissions-bolag" were created by Swedish banks. One of these was Centralgruppens Emissionsbolag with the mission to acquire stakes in new mining companies and to develop mines, thus it was an early junior exploration company. In 1924 the *Boliden Au-Cu-As deposit* was found and was put into production two years later. Some years earlier the Kristineberg deposit in the western part of the Skellefte district had been found using geophysics. During the following years several new massive sulphide deposits was found west of Boliden. Discoveries are still being made in the district, one of the most Cu and Zn-rich deposits ever found in the district, the *Storliden deposit*, was discovered in 1997 by North Atlantic Natural Resources (NAN) and was in production 2002 to 2008.

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Estimation of the number of undiscovered deposits

The result of undiscovered deposit estimated based on MARK3 method are summarised in Table 31 and Figure 71.

Table 31: Summary of the pmf for the number of undiscovered deposits within the permissive tract.

Summary of pmf, number of undiscovered deposits	
Type	CustomMark3
Mean	5.38333
Variance	14.5181
St. Dev.	3.81026
Mode	2
Smallest N deposits in pmf	0
Largest N deposits in pmf	18
Information entropy	2.58685

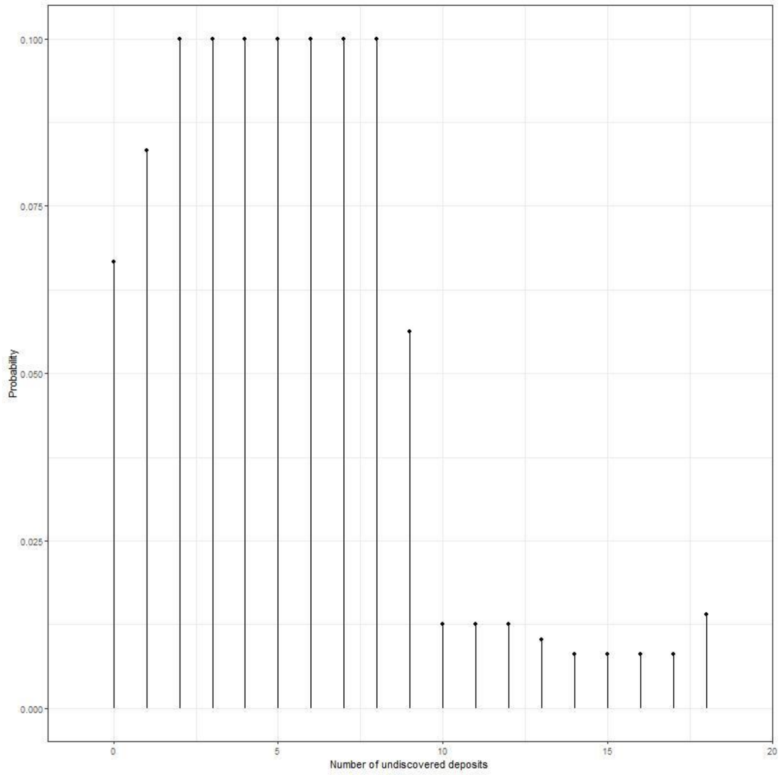

Figure 71: Plot of the estimated probability mass function (pmf) using the negative binomial option.

Assessment of metal tonnages

Undiscovered resources for the tract were calculated by combining the undiscovered deposit estimates with the VMS felsic grade-tonnage model using MAP Wizard software. Results of the Monte Carlo simulation are presented as cumulative frequency plots (Figure 72) and selected simulation results are reported in Table 32. The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralised rock.

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Table 32: Result of Monte Carlo simulations of undiscovered resources in the Eastern Skellefte district tract.

Material	At least the indicated amount at the probability of							Mean	P (0)	P(>mean)
	Q_0.05	Q_0.1	Q_0.25	Q_0.5	Q_0.75	Q_0.9	Q_0.95			
Ore	0	424000	3790000	12400000	29200000	58600000	87200000	24700000	0.0685	0.297
Cu (t)	0	2130.0	23100	83600	222000	495000	788000	224000	0.0685	0.247
Zn (t)	0	7700	89700	342000	922000	2010000	3220000	893000	0.0685	0.257
Ag (t)	0	13.5	139	501	1300	2710	4350	1190	0.0685	0.271

Explanation
" 0.05q" is the 0.05 quantile, " 0.1q" is the 0.1 quantile, and so on. "Mean" is the arithmetic mean. "P (0)" is probability of zero tonnage. "P(>Mean)" is probability that the tonnage exceeds the arithmetic mean.

Comparison between statistics estimated from the multivariate pdf and statistics from analytic formulas:

Mean vectors			Standard deviation vectors			Composite correlation matrix				
	Pdf	Formula		Pdf	Formula		Ore	Cu	Zn	Ag
Ore	24700000	25200000	Ore	43700000	48400000	Ore	NA	0.638	0.684	0.769
Cu	224000	218000	Cu	988000	598000	Cu	0.670	NA	0.260	0.343
Zn	893000	910000	Zn	2510000	2840000	Zn	0.634	0.320	NA	0.825
Ag	1190	1230	Ag	2650	3160	Ag	0.754	0.442	0.730	NA

Explanation
1. The upper triangle of the composite correlation matrix is the upper triangle of the correlation matrix that is estimated from the pdf.
2. The lower triangle of the composite correlation matrix is the lower triangle of the correlation matrix that is calculated with analytic formulas.

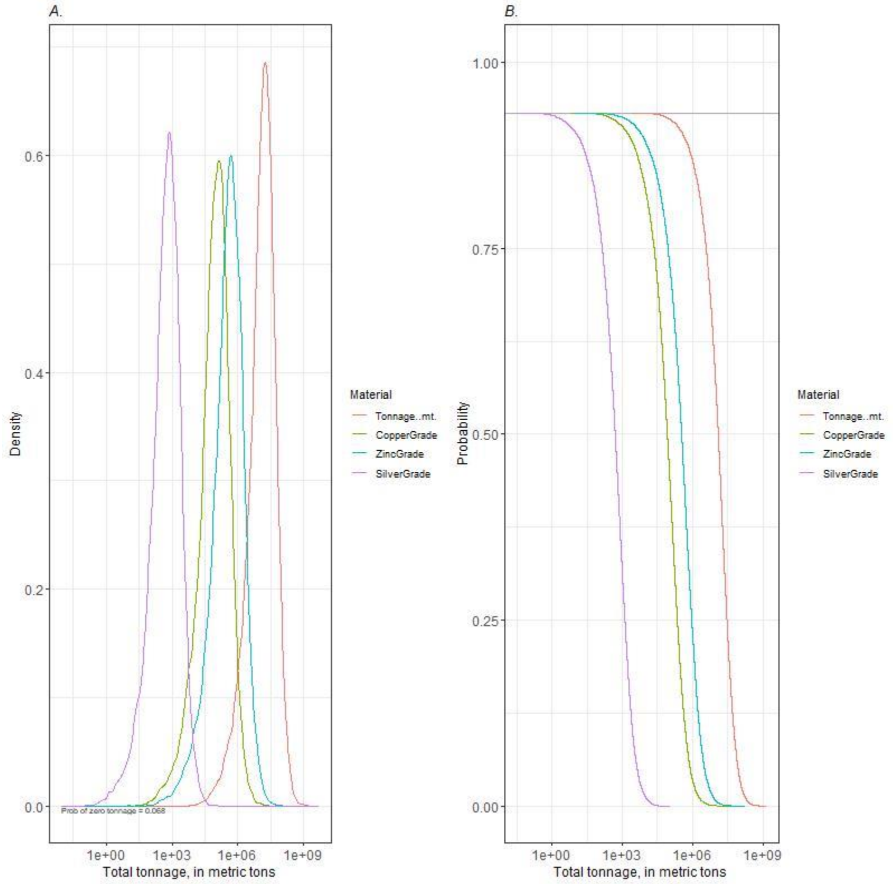

Figure 72: Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in the eastern Skellefte permissive tract.

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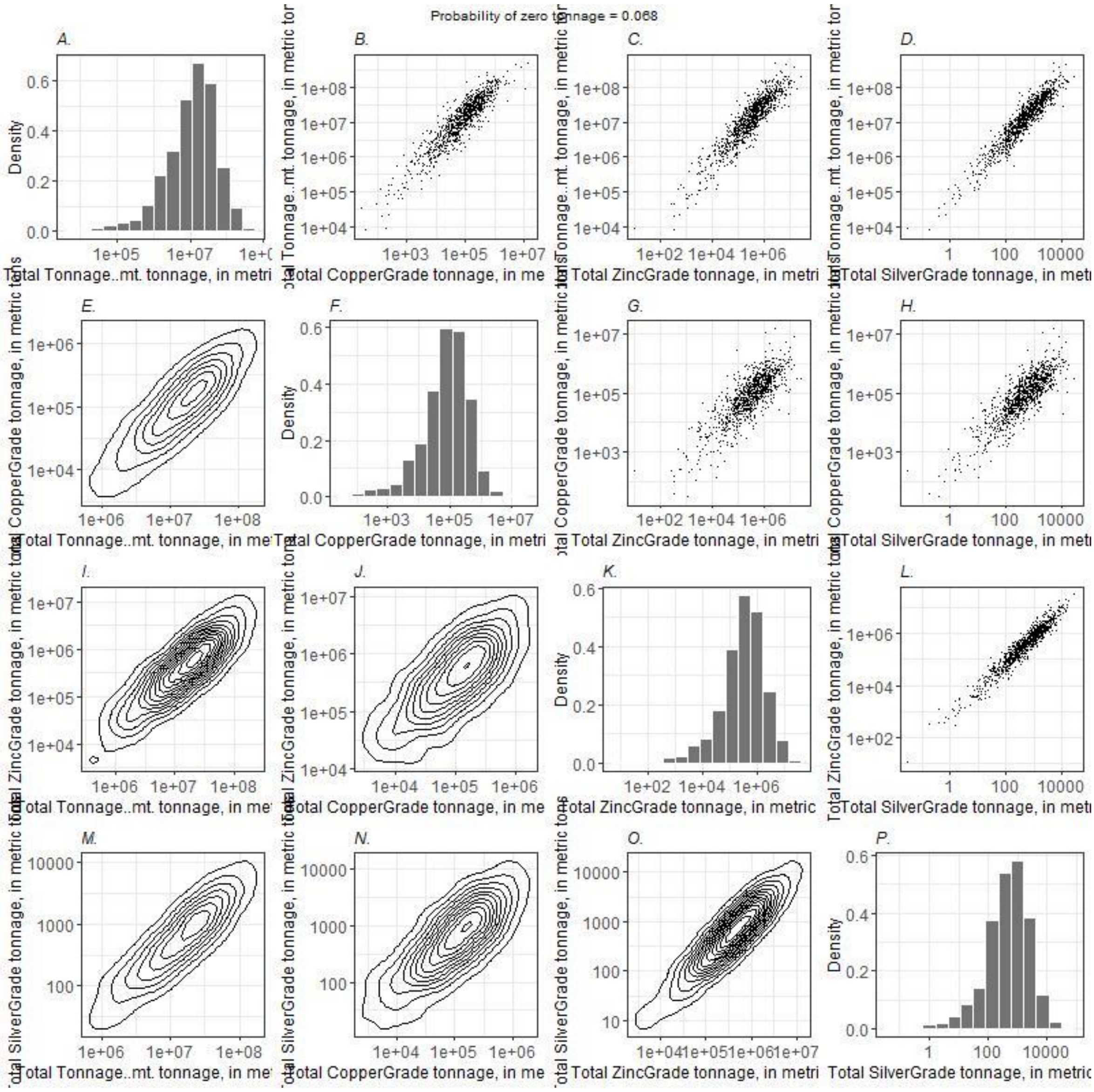

Figure 73: Plots of univariate and bivariate marginal distributions for total ore and metal tonnages in the undiscovered deposits.

5.10. Summary

Mineral resource assessment aims to outline geologically permissive terranes where certain types of mineral deposits likely exist and estimate the amount of metals in the selected tracts and finally estimate the number of undiscovered deposits. With considering of expert's opinion and existing available data on tonnage-grade, we estimated number of undiscovered deposits in this area. The Skellefte district is well-explored for VMS deposits but the result of this study and previous assessments (e.g., Carranza and Sadeghi, 2010) suggest that there are still substantial undiscovered endowments for VMS in this area.

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In Table 33 we have summarized the results of previous assessments and present approach for the estimation of ore tonnage-grade within this area.

Table 33: Summary of the results of previous and present resource assessments for the Skellefte district

Methodology	ONE-LEVEL PREDICTION (MACAMMON ET AL., 1994)	RADIAL –DENSITY FRACTAL ANALYSIS (RAINES, 2008)	3-part method (USGS and MAP project)
Skellefte area	Carranza and Sadeghi (2010)	Carranza and Sadeghi (2010)	This assessment
Ore	95 Mt	97 Mt	80.5 Mt
Copper grade	709 kt	746 Kt	726 Kt
Zinc grade	3190 Kt	3398 Kt	2907 Kt
Silver grade	Not estimated	Not estimated	3.88 Kt
Number of undiscovered deposits	48	50	52

In more specific, details on the estimated ore and tonnage are presented in the table below. We estimated that although the Skellefte district is a well explored area, there is still a substantial undiscovered endowment in the area and has potential to discover several deposits with an average tonnage of more than 1000 kt.

	West	Central	East	Total
Ore	24400000	31400000	24700000	80500000
Cu (t)	222000	280000	224000	726000
Zn (t)	884000	1130000	893000	2907000
Ag (t)	1180	1510	1190	3880

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References

Adamek, P.M., Wilson, M.R., 1979. The evolution of a uranium province in northern Sweden. Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences 291, 355–368.Lundberg, 1980.

Allen, R. L., Weihed, P. & Svenson, S.-Å., 1996: Setting of Zn-Cu-Au-Ag Massive Sulfide Deposits in the Evolution and Facies Architecture of a 1.9 Ga Marine Volcanic Arc, Skellefte district, Sweden. Economic Geology 91, 1022–1053.

Årebäck, H., Barrett, T.J., Abrahamsson, S., Fagerström, P., 2005. The Palaeoproterozoic Kristineberg VMS deposit, Skellefte district, northern Sweden, part I: geology. Mineralium Deposita 40, 351–367.

Assefa, E., 1990. The geology of Långdal mine, Skellefte district, N Sweden. Department of Mineral and Petrology Research Report, 64. Uppsala University. 50 pp.

Barrett T.J., MacLean W.H. & Årebäck H. 2005. The Palaeoproterozoic Kristineberg VMS deposit, Skellefte district, northern Sweden. Part II: chemostratigraphy and alteration. Mineralium Deposita 40, 368–395.

Bauer et al. 2013: A regional scale 3D-model of the Skellefte mining district, northern Sweden. 12th SGA Biennial Meeting 2013. Proceedings, Volume 1.

Bauer, T.E., Paulik, H., Kathol, B. & Pitcairn, I. (eds.), 2013: The Skellefte district, volcanostratigraphy and structures related to Palaeproterozoic base metal deposits. Excursion guidebook SWE1, 12th Biennial SGA Meeting, Uppsala, Sveriges geologiska undersökning, 68 pp.

Bauer, T.E., Skyttä, P., Hermansson, T., Allen, R.L. & Weihed, P., 2014: Comparison of provenance, ore body shape and regional deformation patterns of VMS deposits for mapping the prospectivity in the Skellefte district, Sweden. Mineralium Deposita 19, 555–573.

Bauer T.E., Skyttä P., Hermansson T., Allen R.L. & Weihed P. 2014. Correlation between distribution and shape of VMS deposits and regional deformation patterns, Skellefte district, northern Sweden. Mineralium Deposita 49, 555–573.

Bauer, T.E., Skyttä, P., Hermansson, T., Dehghannejad, M. & Tavakoli, S., 2015: The Skellefte district. In P. Weihed (ed.): 3D, 4D and Predictive Modelling of Major Mineral Belts in Europe. Mineral Resource Reviews, Springer International Publishing Switzerland, 93–121.

Bergman, S., 2018: Regional geology of northern Norrbotten County. In S. Bergman (ed.): Geology of the Northern Norrbotten ore province, northern Sweden. Rapporter och Meddelanden 141, Sveriges geologiska undersökning, 9–17.

Bergman, S., Kübler, L. & Martinsson, O., 2001: Description of regional geological and geophysical maps of northern Norrbotten County (east of the Caledonian orogen). Sveriges geologiska undersökning Ba 56, 110 pp.

Bergman Weihed, J., Bergström, U., Billström, K., Weihed, P., 1996. Geology, tectonic setting, and origin of the Paleoproterozoic Boliden Au–Cu–As deposit, Skellefte district, northern Sweden. Economic Geology 91, 1073–1097.

Billström, K., Weihed, P., 1996. Age and provenance of host rocks and ores in the Paleoproterozoic SkelleftеDistrict, NorthernSweden. EconomicGeology 91, 1054–1072.

Carranza E J M, Sadeghi M (2010). Predictive mapping of prospectivity and quantitative estimation of undiscovered VMS deposits in Skellefte district (Sweden). Ore Geol Rev, 38(3): 219–241.

Carranza E J M, Sadeghi M (2014). Post-VMS mineralization deformations (1880–1820 Ma) of the Skellefte district (Sweden): insights from the spatial pattern of VMS occurrences. Front.Earth Sci., v 8, issue 3, 319-324.

Chevalier A. 1999. Storliden – a newly discovered Cu-Zn deposit in the western Skellefte district. In: Cook N.J. & Sundblad K. (eds) Precambrian Gold in the Fennoscandian and Ukrainian Shields and Related Areas. Geological Survey of Norway, Gold 99, Trondheim, 4–6 May 1999. Abstract Volume, 58–59.

Du Rietz, T., 1951, Geology and ores of the Kristineberg deposit, Vesterbotten, Sweden, SGU C 524.

Gohl, K., Pedersen, L.B., 1994. Collisional tectonics of the Baltic Shield in the northern Gulf of Bothnia from seismic data of the BABEL project. Geophysical Journal International 120, 209–226.

Hallberg, A., S023 SKELLEFTE DISTRICT Zn-Cu-Pb-Ag-Au. in Eilu, P. (ed.) 2012. Mineral deposits and metallogeny of Fennoscandia. Geological Survey of Finland, Special Paper 53, 401 pages, 248 figures, 105 tables.

Hietanen, A. 1975. Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian of Finland. U.S. Geological Survey Journal of Research 3, 631−645.

Kathol, B. & Weihed, P. (eds.), 2005: Description of regional geological and geophysical maps of the Skellefte district and surrounding areas. Sveriges geologiska undersökning Ba 57, 197 pp.

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Kathol, B., Weihed, P., Antal Lundin, I., Bark, G., Bergman Weihed, J., Bergström, U., Billström, K., Björk, L., Claesson, L., Daniels, J., Eliasson, T., Frumerie, M., Kero, L., Kumpulainen, R.A., Lundström, H., Lundström, I., Mellqvist, C., Petersson, J., Skiöld, T., Sträng, T., Stølen, L.-K., Söderman, J., Triumf, C.-A., Wikström, A., Wikström, T. & Årebäck, H., 2005: Regional geological and geophysical maps of the Skellefte district and surrounding areas. Bedrock map. Sveriges geologiska undersökning Ba 57:1.

Lundqvist, T., 1987. Early Svecofennian stratigraphy of southern and central Norrland, Sweden, and the possible existence of an Archaean basement west of the Svecokarelides. Precambrian Research 35, 343–352.

Lundström, I., Persson, P. O., and Bergström, U. (1999). Indications of early deformational events in the north-eastern part of the Skellefte field. Indirect evidence from geological and radiometric data from the Stavaträsk-Klintån area, Boliden map-sheet. Radiometric dating results, 4, 52-69. Research Papers. SGU series C 831.

Lundström, I. & Antal, I., 2000: Bedrock map 23K Boliden, scale 1 : 50 000. Sveriges geologiska undersökning Ai 110–113.

Nitronen, M., 1997. The Svecofennian Orogen: a tectonic model. Precambrian Research 86, 21–44.

Öhlander, B., Skiöld, T., Elming, S.-Å., Claesson, S., Nisca, D.H., BABEL Working Group, 1993. Delineation and character of the Archaean–Proterozoic boundary in Northern Sweden. Precambrian Research 64, 67–84.

Rickard, D.T., Zweifel, H., 1975. Genesis of Precambrian sulfide ores, Skellefte District, Sweden. Economic Geology 70, 255–274.

Sadeghi, M., Kathol, B, Bastani, M., Lax, K. 2008. Application of GIS to integration of SGU data base: predictive prospectivity mapping of volcanic massive sulphide potential in the Skellefte District. Sveriges Geologiska Undersökning, Rapport 2008:30. 122 pp.

Skyttä, P., Bauer, T., Tavakoli, S., Hermansson, T., Andersson, J. & Weihed, P., 2012a: Evolution of early-orogenic deformation zones and their significance for the development of contrasting structural domains within the Palaeoproterozoic Skellefte district, Sweden. Geophysical Research Abstracts 14, EGU2012–14180, EGU General Assembly 2012.

Skyttä, P., Bauer, T.E., Tavakoli, S., Hermansson, T., Andersson, J. & Weihed, P., 2012b: Pre-1.87 Ga development of crustal domains overprinted by 1.87 Ga transpression in the Palaeoproterozoic Skellefte district, Sweden. Precambrian Research 206–207, 109–136.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Skyttä, P., Hermansson, T., Elming, S-A. & Bauer, T., 2010: Magnetic fabrics as constraints on the kinematic history of a pretectonic granitoid intrusion, Kristineberg, northern Sweden. Journal of Structural Geology 32, 1125–1136.

Skyttä, P., Hermansson, T., Andersson, J., Whitehouse, M. & Weihed, P., 2011: New zircon data supporting models of short-lived igneous activity at 1.89 Ga in the western Skellefte district, central Fennoscandian Shield. Solid Earth 2, 205–217.

Skyttä, P., Bauer, T., Hermansson, T., Dehghannejad, M., Juhlin, C., Garcia Juanatey, M., Hübert, J. & Weihed, P., 2013: Crustal 3-D geometry of the Kristineberg area (Sweden) with implications on VMS deposits. Solid Earth 4, 387–404.

Stephens, M.B., Wahlgren, C.-H. & Weihed, P., 1997: Sweden. In E.M. Moores & R.W. Fairbridge (eds.) Encyclopedia of European and Asian Regional Geology, Chapman & Hall, 690–704.

Stephens, M.B., Ripa, M., Lundström, I., Persson, L., Bergman, T., Ahl, M., Wahlgren, C.-H., Persson, P.-O. & Wickström, L., 2009: Synthesis of the bedrock geology in the Bergslagen region, Fennoscandian Shield, south-central Sweden. Sveriges geologiska undersökning Ba 58, 259 pp.

Talbot, C. J., 1988. A desk analysi of the tectonic history of the Långdal mine, Skellefte district, Sweden. Economic Geology 83, 647-656.

Tavakoli, S., Bauer, T. E., Rasmussen, T. M., Weihed, P. & Elming, S.-Å., 2016: Deep massive sulphide exploration using 2D and 3D geoelectrical and induced polarization data in Skellefte mining district, northern Sweden. Geophysical Prospecting 64, 1602-1619.

Tegengren, F.R. & Johansson, H.E., 1924: Sveriges ädlare malmer och bergverk. Sveriges geologiska undersökning Ca 17, 1–400.

Weihed, P., Sorjonen-Ward, P., Bergman Weihed, J., Mattsson, B., 2002. Post deformation sulphide-quartz vein gold mineralization in the footwall alteration zone of the Palaeoproterozoic Långdal VMS deposit, Skellefte district, northern Sweden. Geologiska Föreningens i Stockholm Förhandlingar 124, 201–210.

Weihed, P., Bergman, J., Bergström,U., 1992. Metallogeny andtectonic evolution of the Early Proterozoic Skellefte district, northern Sweden. Precambrian Research 58, 143–167.

Willdén, M., 1986. Geology of the western part of the Skellefte field and the Kristineberg and Hornträsk sulphide deposits. 7th IAGOD Symposium, Excursion Guide No. 4: Sveriges Geologiska Undersökning, Ca, 62, pp. 46–54.

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Wilson, M.R., Hamilton, P.J., Fallick, A.E., Aftalion, M., Michard, A., 1985. Granites and early crustal evolution in Sweden: evidence from Sm–Nd, U–Pb, and O isotope systematics. Earth Planetary Science Letters 72, 376–388.

Wilson, M.R., Sehlstedt, S., Claesson, L.-Å., Smellie, J.A.T., Aftalion, M., Hamilton, P.J., Fallick, A.E., 1987. Jorn: an early Proterozoic intrusive complex in a volcanic-arc environment, north Sweden. Precambrian Research 36, 201–225.

Zweifel, H., 1982. Ore deposits in the Skellefte field — volcanic activity and depositional environment. Geologiska Föreningens i Stockholm Förhandlingar 104, 369.

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APPENDIX – Grade and tonnage data for the VMS subclasses

Mafic Subclass

ID	Name	Ore	Cu	Zn
CA1	Betts Cove	120000	10	5
NO40	Øvre Nomilålgi	150000	0.88	1
CA33	York Harbour	240000	2.4	7
NO59	Svanøy	250000	0.84	1
NO47	Ytterøya	460000	1.9	2.4
NO35	Ingeborgvatn	500000	1.5	1
NO37	Vågedalen	700000	1	2.1
NO60	Vaddas	715000	1.37	0.01
NO32	Åsoren	730000	1.43	1.32
NO46	Høydal	1059000	1.15	0.45
US2	Stone Hill	1300000	0.64	1.0
NO43	Vigsnes	1440000	1.66	1.4
NO58	Grimeli	1500000	2	1
NO55	Bursi	1845000	1.5	0.31
NO54	Sagmo	2160000	1.6	0.23
NO53	Mons Petter	2500000	1.75	0.48
NO42	Rødkleiv	2646000	0.78	1.71
NO38	Rieppe	3000000	0.5	2
NO52	Charlotta	3100000	2	0.58
NO51	Jakobsbakken	4500000	1.55	2.42
NO50	Ny Sulitjelma	5790000	1.675	0.485
NO49	Giken	10500000	2.25	0.7
NO45	Tverrfjellet	19000000	1	1.2
NO41	Joma	22453000	1.49	1.45
NO44	Løkken	30000000	2.3	1.8
SW27	Remdalen	737389	1.43	2.74
CA1	Betts Cove	120000	10	5
NO40	Øvre Nomilålgi	150000	0.88	1
CA33	York Harbour	240000	2.4	7
NO59	Svanøy	250000	0.84	1
NO47	Ytterøya	460000	1.9	2.4
NO35	Ingeborgvatn	500000	1.5	1
NO37	Vågedalen	700000	1	2.1
NO60	Vaddas	715000	1.37	0.01
NO32	Åsoren	730000	1.43	1.32
NO46	Høydal	1059000	1.15	0.45
US2	Stone Hill	1300000	0.64	1.0
NO43	Vigsnes	1440000	1.66	1.4
NO58	Grimeli	1500000	2	1
NO55	Bursi	1845000	1.5	0.31
NO54	Sagmo	2160000	1.6	0.23
NO53	Mons Petter	2500000	1.75	0.48
NO42	Rødkleiv	2646000	0.78	1.71
NO38	Rieppe	3000000	0.5	2
NO52	Charlotta	3100000	2	0.58
NO51	Jakobsbakken	4500000	1.55	2.42
NO50	Ny Sulitjelma	5790000	1.675	0.485
NO49	Giken	10500000	2.25	0.7
NO45	Tverrfjellet	19000000	1	1.2
NO41	Joma	22453000	1.49	1.45
NO44	Løkken	30000000	2.3	1.8
SW27	Remdalen	737389	1.43	2.74

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Bimodal-Mafic subclass

ID	Name	Ore	Cu	Zn
NO29	Åkervoll	25000	1.5	20
NO27	Nygruva	49000	0.7	3.4
NO15	Skrattåsen	85000	1	7
NO24	Gressli	85000	0.9	5.5
NO23	Mannfjell	100000	1.8	5.3
US16	Ore Hill	100000	0.5	21
US5	Little Bob	140000	1.0	1.5
CA54	Louvicourt	140000	0.42	1.07
NO22	Vingelen gruve	230000	1.3	3.8
NO12	Godejord	250000	0.6	4.2
NO13	Finnbu	250000	0.3	3
NO14	Raudvatnet	365000	0.49	2.5
NO9	Sivilvangen	400000	0.69	4.31
NO30	Valaheien	484000	0.27	0.1
NO20	Nygruva	500000	0.85	3.5
NO21	Søndre Geitryggen	500000	0.8	2.4
US15	Milan	500000	2.25	7.26
NO11	Visletten	780000	0.92	3.86
CA23	Rambler-Main	960000	1.38	1.99
NO26	Gjersvik	1620000	2.15	0.6
CA9	Daniel's Pond	1690000	0.57	8.37
NO18	Folldal	2000000	1.9	1.1
US1	Pyriton	2750000	1.2	0.5
NO8	Hersjøgruva	2994000	1.7	1.4
NO17	Nordre Geitryggen	3000000	1.3	3.2
NO16	Killingdal	3242000	1.7	5.5
US11	Ledge Ridge	3700000	0.95	2.3
NO10	Skiftesmyr	4070000	1	1.5
US12	Pickett Mountain	4100000	1.3	10.4
CA22	Rambler-East	4470000	1.71	0.14
NO6	Bleikvassli	6000000	0.15	4
NO25	Skorovas	6900000	1.14	2.71
NO7	Grimsdalen	8290000	0.5	2.3
CA21	Point Leamington	16560000	0.5	2
US8	Bald Mountain	30000000	1.0	1.1

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Bimodal-Felsic and Felsic subclass

ID	Name	Ore	Cu	Zn
SW4	Doranåje	50000	2.48	0.17
SW5	Gelvenåkko	50000	1.84	1.63
SW1	Kittelgruvan	115600	0.32	3.2
NO4	Mos gruve	122000	0.5	1.1
SW2	Björkvattnet	132674	0.73	0.4
SW6	Tjokkola	169000	0.89	2.2
SW3	Beitsetjenjunje	219215	0.97	1
US26	New Canton	250000	2.0	1.0
NO2	Båsmo	2550000	0.13	0.14
NO1	Sølvberget	4000000	0.4	1.6
SW7	Levimalmen	5100000	1.2	1.8
NO3	Mofjellet	5350000	0.31	3.61
US25	Mineral	9100000	0.5	3.0
SW9	Jervas	10000000	0.46	0.07
SW8	Stekenjokk	11900000	1.3	3.8
US6	Tallapoosa	90000	1.9	2.9
US10	Emerson	150000	0.23	3.16
CA63	Rocky Turn	260000	0.3	7.0
CA48	Headway	280000	1.43	6.2
CA53	Key Anacon East	290000	0.65	4.36
CA61	Pabineau River	360000	1.36	5.5
CA59	North Boundary	460000	0.6	9.0
US23	Andersonville Zone 24	500000	0.98	4.87
US4	Jenny Stone	570000	1.0	0.7
CA47	Halfmile Lake North	600000	0.49	6.78
US14	Davis	700000	1.3	5.5
US22	Andersonville Zone 18	720000	0.6	4.68
CA30	Tulk's Pond	720000	1.3	5.6
US13	Harborside	730000	1.25	5.5
CA62	Restigouche	860000	0.33	7.07
CA36	Austin Brook	900000	0.1	2.93
US3	Chestatee	1100000	1.0	0.7
CA34	Stirling	1240000	0.72	6.37
CA56	Mt. Fronsac North	1260000	0.14	7.65
CA51	Heath Steele (E-F)	1400000	1.51	4.39
CA67	Wedge	1460000	2.4	1.75
CA52	Key Anacon	1670000	0.14	6.02
CA39	Canoe Landing	1790000	0.77	2.67
CA66	Tomogonops	2040000	0.59	6.29
CA64	Stratmat	2360000	0.34	7.92
CA6	Buchans (Old Buchan-Oriental)	2590000	1.4	17
CA58	Nepisiguit	2640000	0.28	2.3
CA35	Armstrong A	3180000	0.29	2.29
US7	Alder Pond	3400000	2.2	9.0
CA5	Buchans (McLean)	3770000	1.29	14.5
UK1	Parys Mountain	4114000	1.46	2.4
CA49	Heath Steele (A-C-D)	4780000	1.0	5.34
CA46	Halfmile Lake	5660000	0.19	8.27
CA4	Buchans (Lucky Strike-Rothermere)	9070000	1.3	16.3
CA38	Brunswick No. 6	12500000	0.37	5.61
CA42	Chester	16240000	0.77	0.19
CA57	Murray Brook	23400000	0.44	1.79
CA50	Heath Steele (B)	40420000	1.11	4.71
CA41	Caribou	70000000	0.5	4.3
CA37	Brunswick No. 12	137300000	0.33	9.56

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Siliciclastic-Mafic subclass

ID	Name	Ore	Cu	Zn
SW29	Skidträskbäcken N	14000	0.46	0.1
SW28	Skidträskbäcken	23000	0.71	1.53
SW37	Svavelkismalmen	54300	0.02	0.05
NO69	Fosgruva	64000	1.3	1.1
SW34	Abelvattnet	68892	0.9	0.07
NO72	Lillefjell	107000	5	4.5
NO79	Kvernenglia	142000	0.3	2
SW30	Rikarbäcken	150000	0.8	4.3
SW31	Storbäcksdalen Västra	150000	1.2	6.3
SW32	Tjåter	150000	1	4.8
SW33	Usmeten	246017	1.28	0.31
NO71	Kjøli	250000	2.1	0.1
NO73	Fløttum	350000	0.96	4.76
NO63	Røstvangen	488000	3.09	0.73
SW36	Jormlien	612000	0.4	4.75
NO64	Melkedalen	650000	1	2.2
NO80	Muggruva	650000	1.1	0.25
SW38	Ankarvattnet	753383	0.45	5.48
NO78	Fjellsjø	800000	0.83	2.42
NO76	Lergruvbakken	970000	0.63	7
NO68	Undal	1000000	1.15	1.86
SW35	Unna Gaisartjåkko	1000000	0.8	0.5
NO75	Kongens gruve	1183000	3.2	4.2
US18	Ducktown	1200000	0.7	1.2
US19	Elizabeth	2910000	1.8	0.5
NO74	Storwartz	5000000	3	9.4
NO70	Bjørkåsen	6000000	0.45	1
NO81	Stordø	9000000	0.11	0.28
US24	Gossan Lead	18100000	0.5	2.0
US17	Ducktown	19090000	1.6	1.2
SW29	Skidträskbäcken N	14000	0.46	0.1
SW28	Skidträskbäcken	23000	0.71	1.53
SW37	Svavelkismalmen	54300	0.02	0.05
NO69	Fosgruva	64000	1.3	1.1
SW34	Abelvattnet	68892	0.9	0.07
NO72	Lillefjell	107000	5	4.5
NO79	Kvernenglia	142000	0.3	2
SW30	Rikarbäcken	150000	0.8	4.3
SW31	Storbäcksdalen Västra	150000	1.2	6.3
SW32	Tjåter	150000	1	4.8
SW33	Usmeten	246017	1.28	0.31
NO71	Kjøli	250000	2.1	0.1
NO73	Fløttum	350000	0.96	4.76
NO63	Røstvangen	488000	3.09	0.73
SW36	Jormlien	612000	0.4	4.75
NO64	Melkedalen	650000	1	2.2
NO80	Muggruva	650000	1.1	0.25
SW38	Ankarvattnet	753383	0.45	5.48
NO78	Fjellsjø	800000	0.83	2.42
NO76	Lergruvbakken	970000	0.63	7
NO68	Undal	1000000	1.15	1.86
SW35	Unna Gaisartjåkko	1000000	0.8	0.5
NO75	Kongens gruve	1183000	3.2	4.2
US18	Ducktown	1200000	0.7	1.2
US19	Elizabeth	2910000	1.8	0.5
NO74	Storwartz	5000000	3	9.4
NO70	Bjørkåsen	6000000	0.45	1
NO81	Stordø	9000000	0.11	0.28
US24	Gossan Lead	18100000	0.5	2.0
US17	Ducktown	19090000	1.6	1.2

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