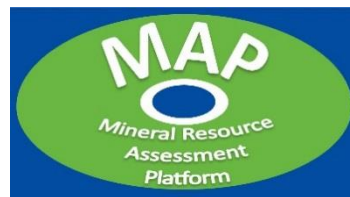


# MapWizard Method and Data Guide

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## Content

<b>1. Assessment method and process .....</b>	<b>5</b>
1.1. Purpose of assessment .....	5
1.2. Assessment categories .....	5
1.3. Terminology .....	6
1.4. Three-part assessment method .....	7
Overview of method .....	7
Deposit models .....	8
Permissive tracts .....	9
Number of undiscovered deposits .....	10
Quantitative resource analysis .....	11
1.5. The assessment process .....	11
Pre-assessment meeting tasks .....	13
Assessment meeting .....	14
1.6. Reporting of results .....	16
1.7. References .....	16
<b>2. Grade-tonnage model data .....</b>	<b>20</b>
2.1. Parameters to record .....	20
2.2. Sampling unit .....	21
2.3. Pre-mining resource and reserve data .....	21
2.4. Spatial rule .....	21
2.5. Grade information and missing values .....	21
2.6. Common sources of biased models and reasons to review the data .....	22
<b>3. Spatial data for fuzzy logic and weights of evidence computations .....</b>	<b>23</b>
3.1. Suitable datasets .....	23
Geophysical evidence .....	24
Geochemical evidence .....	25
Geological evidence .....	26
3.2. Pre-processing of the data for MapWizard fuzzy logic and weights of evidence tools ...	27
Fuzzy logic .....	27
Weights of evidence .....	30
<b>4. Tract delineation process .....</b>	<b>32</b>
4.1. Introduction .....	32
4.2. Experts tracts and VMS occurrences .....	33
4.3. Fuzzy logic delineation of permissive tracts .....	35

4.4. Suggested delineation process using mineral prospectivity modelling techniques..... 38

# 1. Assessment method and process

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Numerous methods have been applied to estimation of undiscovered mineral resources during the past several decades, but the process remains challenging and there are no universally accepted, definitive procedures exist (Lisitsin et al. 2007 and references therein). The procedure described in this document is based on the three-part quantitative assessment method (Singer 1993, Singer and Menzie 2010). The method has been thoroughly evaluated (Harris and Rieber 1993, Barton et al 1995, Drew 1997), and it uses statistical techniques of data analysis and integration and treats and expresses uncertainty. It is flexible to use varying amounts of objective geological data and subjective expert knowledge and it generates reproducible assessment results.

This section describes the assessment method and process, concentrating on technical aspects and tasks that must be performed and guidelines and rules that should be followed. The document does not consider the administrative aspects of an assessment project or how the work is organized but assumes that the required personnel and other resources are available.

## 1.1. Purpose of assessment

The purpose of the assessments is to provide unbiased estimates of the amount of undiscovered metals within the area of interest, down to a selected depth.

The estimates can be used, for example, for national and regional planning for land use, natural resources management and environmental planning. The assessments will enable accounting of metallic natural resources according to the principles of sustainable development and they will produce new information for metallogenic and lithologic research.

## 1.2. Assessment categories

The classification of resources is presented in Figure 1.1. Resources can be classified according to geologic certainty of existence (x axis) and economic feasibility of extraction (y axis). Assessments only indirectly take into account the economic, technical, social or environmental factors that might affect the potential for economic extraction of a metal. Hence, part of the estimated undiscovered resources may be in subeconomic occurrences.

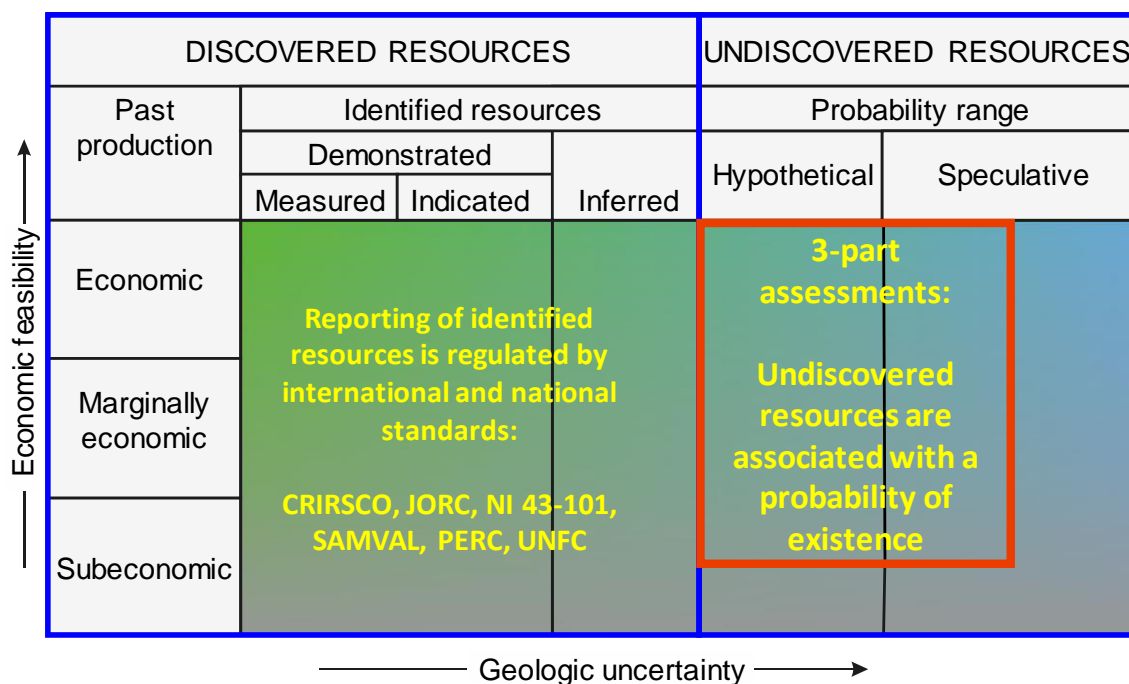


Figure 1.1. Classification of mineral resources used in GTK assessments (modified from U.S. Geological Survey National Mineral Resource Assessment Team 2000). Geologic certainty (x axis) increases to the right and economic feasibility increases (y axis) upwards.

### 1.3. Terminology

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

#### **Mineral deposit**

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

#### **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 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.

**Resource**

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

**Identified resources**

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

**Undiscovered resources**

Resources in undiscovered mineral deposits whose existence is postulated based on indirect geologic evidence.

**Hypothetical resources**

Undiscovered resources in known types of mineral deposits postulated to exist in favourable geologic settings where other deposits of the same types are known.

**Speculative resources**

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

**Discovered resources**

The total amount of identified resources and cumulative past production.

## 1.4. Three-part assessment method

### Overview of method

The three-part quantitative assessment method (Singer and Ovenshine 1979, Singer 1993, Barton et al. 1995, Drew 1997, Singer 2007, Singer and Menzie 2010) was designed to provide quantitative estimates on undiscovered mineral resources in particular areas. The results are expressed as the total metal endowment and the number of undiscovered deposits. Economic analysis can be applied to acquire monetary value of the undiscovered resources.

The three-part method consists of the following components: (1) Evaluation and selection or construction of descriptive models and grade-tonnage models for the deposit types, (2) delineation of areas according to the types of deposits permitted by the geology (permissive

tracts), and (3) estimation of the number of undiscovered deposits of each deposit type. The estimated number of deposits is combined with the grade and tonnage distributions to model the total undiscovered metal endowment.

To ensure internal consistency of the method, delineated tracts must be consistent with descriptive models, grade-tonnage models must be consistent with descriptive models and with known deposits in the area, and estimates of number of deposits must be consistent with grade-tonnage models. Lack of consistency between the grade-tonnage model and the number of deposits estimate can introduce serious bias into the estimates. Also flawed grade-tonnage models can produce bias in the estimates.

## Deposit models

Deposit models are the cornerstone of the three-part quantitative assessment method. They are used to classify mineralized and barren environments, as well as types of known deposits, and to discriminate mineral deposits from mineral occurrences (Singer and Berger 2007). Only deposit models designed for quantitative assessments are discussed in this document (e.g., Cox and Singer 1986, Bliss 1992a, Rogers et al. 1995).

Several types of deposit models can be used in the three-part assessment method: descriptive models, grade-tonnage models, deposit density models, economic models and quantitative descriptive models (Singer and Berger 2007). Descriptive models and grade-tonnage models are required for the procedure followed by MAP assessments. Deposit density models can be used in the estimation of the number of undiscovered deposits if suitable models exist. Economic models can be used to obtain information of the economically viable proportion of the total estimated undiscovered endowment.

### Descriptive models

A mineral deposit model consists of systematically arranged information describing some or all of the essential characteristics of a class of mineral deposits (Barton, 1993). Usually a descriptive model consists of two parts. The first part describes the geologic environments in which the deposits occur. It contains information on favourable host rocks as well as possible source rocks, age ranges of mineralization, depositional environment, tectonic setting and associated deposit types. This part of the descriptive model plays a primary role in the delineation of tracts of land where the geology permits the occurrence of undiscovered deposits.

The second part of the model lists essential identifying characteristics of the deposit type, with emphasis on aspects by which the deposits might be recognized, including mineralogy, alteration and geochemical and geophysical signatures. The second part is used to classify known deposits and occurrences into types. Identifying the types of known deposits is important for the tract

delineation process, and it can sometimes help delineate geologic environments not indicated on geologic maps.

The descriptive model used for a deposit type must be consistent with the grade-tonnage model for the same deposit type.

### **Grade-tonnage models**

A grade-tonnage model for a deposit type displays the frequency distributions of tonnages and average grades of well-studied and completely delineated deposits of the type. 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. These models are based on data of average metal grades and the associated tonnage combining the total production and resources (including reserves) at the lowest possible cut-off grade. Grade-tonnage models are combined with estimates of number of undiscovered deposits to achieve an assessment of the amount of undiscovered metals.

### **Deposit density models**

Estimation of the number of undiscovered deposits within a tract is an essential component of the three-part assessment method. Many different techniques can be used to make these estimates, but mineral deposit density models are the most robust approach (Singer and Berger 2007). A mineral deposit density model (Bliss 1992b, Bliss and Menzie 1993, Singer 1994, Singer et al 2001, Singer et al 2005) displays as a frequency distribution the number of deposits of a certain type per unit area within well-explored areas. Many of these areas can be considered to provide information on what should be high estimates of number of undiscovered deposits in most cases (Singer and Berger 2007). Hence, deposit density models are probably best used as guides to upper limits of deposit densities.

When a deposit density model is used, it is important to make sure that the model is consistent with the descriptive and grade-tonnage models.

### **Permissive tracts**

A permissive tract is an area within which the geology permits the existence of mineral deposits of one or more specific types (Singer 1993). It is important to distinguish between areas favourable for the existence of deposits and permissive tracts; the former are only a subset of the latter. Permissiveness of a tract does not indicate any favourability for the occurrence of deposits, and it has nothing to do with the likelihood of discovery of existing undiscovered deposits.

Permissive tracts are based on criteria derived from descriptive models. Tract boundaries are defined so that the probability of deposits of the type delineated occurring outside of the tract is negligible. In three-part assessment, 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 parts of the tract. Original tract boundaries are reduced only where it can be firmly demonstrated that a deposit type could not exist. This evidence could be based on geology, knowledge about unsuccessful exploration, or the presence of barren overburden exceeding the predetermined delineation depth limit.

### Number of undiscovered deposits

The third part of a three-part assessment is the estimation of the number of undiscovered deposits of each type that exist in the delineated tracts. This number of deposits is not known with certainty and the estimates represent the probability that a certain fixed but unknown number of undiscovered deposits exist in the delineated tracts. The estimates are done by deposit type and they must be consistent with the grade-tonnage model, e.g., half of the estimated number of deposits must be larger than the median tonnage given by the grade-tonnage model (Singer, 1993). The estimates must also be consistent with the areal rules used in the grade-tonnage model to define a deposit. Well-explored deposits in the tract for which published grade and tonnage values exist are considered as discovered deposits, whereas known deposits 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 frequency of deposits in well-explored areas, local deposit extrapolations, counting and assigning probabilities to anomalies, process constraints, relative frequencies of associated deposit types, area spatial limits, and total known metal (Singer 2007). Some of these methods produce a single estimate of the expected (mean) number of deposits; others produce a probability distribution of the expected number of deposits. In the latter case, the spread of the number of deposits estimates associated with high and low quantiles of the probability distribution (for example, the 90 percent and 10 percent 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 favourability of the existence of a deposit type.

Typically, estimates are made subjectively by a team of experts knowledgeable about the deposit type and the geology of the region. Each expert makes an estimate independently and the estimates are discussed to reach a final consensus estimate.

Sensitivity analysis shows that changes in grade and tonnage estimates have a much larger influence on the change in expected metal content than changes in the expected number of deposits have (Singer and Kouda 1999). This indicates that selection of the proper grade-tonnage model is more critical to the assessment results than small errors in estimates of the number of deposits.

## Quantitative resource analysis

The parts of the assessment method described above produce consistent estimates of the probability distribution of grades and tonnages of the deposits and of the number of undiscovered deposits in the delineated area. As the final step of the assessment, these estimates are combined using statistical methods to achieve a probability distribution of the quantities of contained metals and ore tonnages in undiscovered deposits.

### 1.5. The assessment process

The assessment is performed by a team consisting of members familiar with the assessment method and members with expertise in the deposit type(s) being assessed and the geology of the areas of interest. The assessment process includes both tasks that individual scientists perform by themselves and tasks that require teamwork of several experts. A central part of the process is the assessment meeting, in which a team of experts evaluates previously defined permissive tracts and estimates the number of undiscovered deposits in these tracts. Preparatory tasks that must be completed before the meeting include data gathering and definition of permissive tracts. After the meeting, the results will be compiled into a report.

Most of the experts on various metals and geology of different areas are not familiar with the assessment method. Hence, it is important to arrange a start-up meeting in the beginning of an assessment process, where the method is explained in such detail that the assessment team members can perform their tasks according to the guidelines in this document.

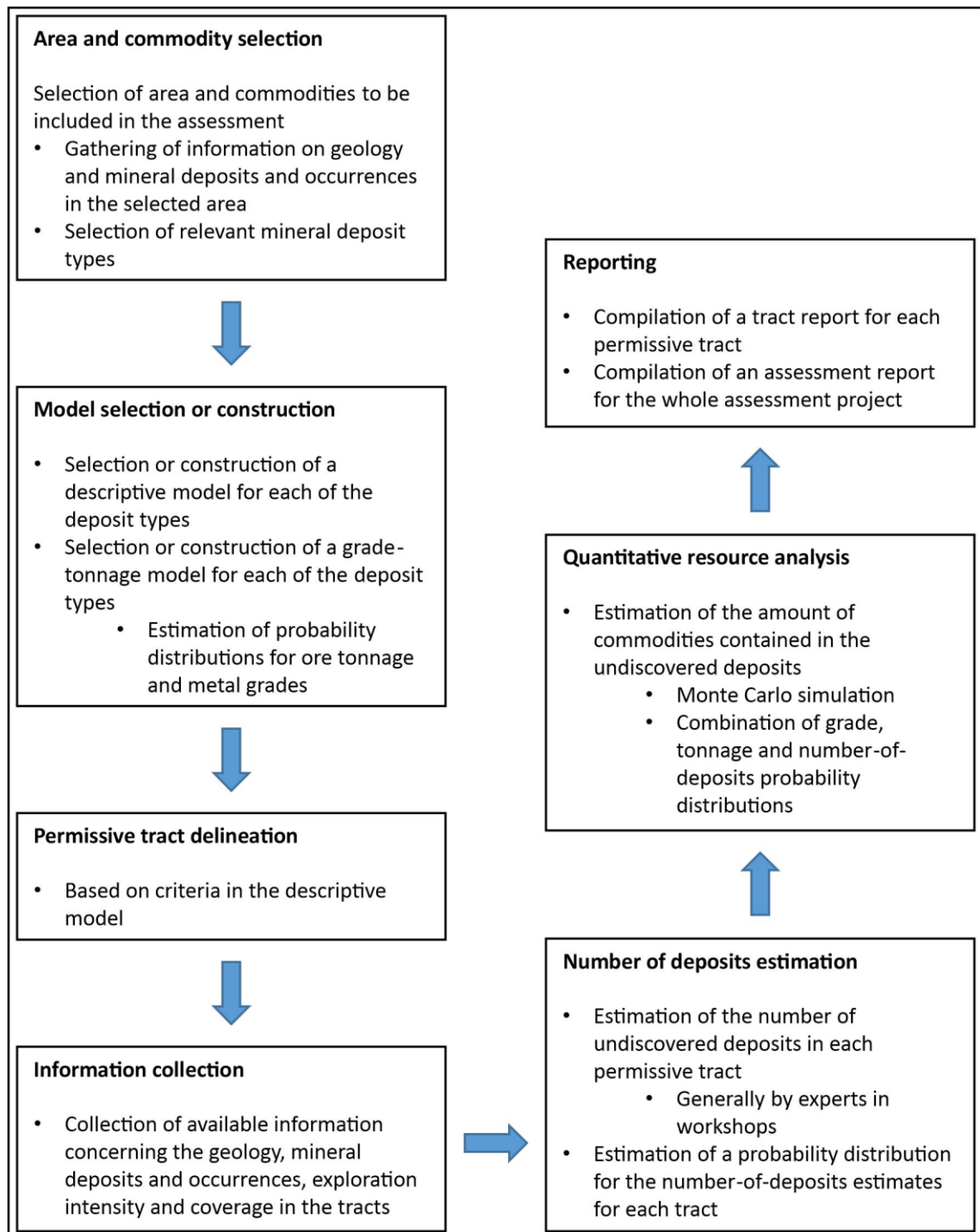


Figure 1.2. Process flow of a typical three-part assessment project.

## Pre-assessment meeting tasks

The pre-assessment meeting tasks include:

- Gathering and compiling available information on known deposits in the area of interest
- Gathering and compiling geological maps of the areas of interest
- Selection of appropriate deposit models (descriptive, grade-tonnage)
- Gathering and compiling exploration information for the metal and deposit types
- Delineation of permissive tracts for the deposit types

These tasks are carried out by various members of the assessment team. The results are compiled into electronic databases and GIS maps. It is essential that all these results are distributed to the whole team already during the pre-assessment meeting phase. This ensures that similar standards are used during the work and all new information immediately comes to the attention of all members of the team. It also facilitates the adjustment of the results based on discussion within the team. The team members must be familiar with the results of the preliminary tasks before the assessment meeting.

### **Gathering and compiling available information on known deposits**

The work begins by gathering the available data on known deposits and occurrences significant for the metal under assessment. These data include information on the location and geological, geochemical and geophysical characteristics of the deposits and occurrences as well as grade and tonnage data for well-studied deposits. Information on indications of mineralization, like geochemical and geophysical anomalies and ore boulders, should also be gathered. The data is used in the selection or development of appropriate deposit models and in the delineation of permissive tracts. It is important that the deposit and occurrence data is gathered so that it is consistent with the data in the descriptive models and grade-tonnage models. For example, the spatial rules to define the limits of a deposit must be followed when compiling grade and tonnage data.

### **Gathering and compiling geological maps of the areas of interest**

The overall scale of the assessment should be based on the scale of available geological maps. All maps should be made available in GIS format.

### **Selection of appropriate descriptive and grade-tonnage models**

In the beginning of the assessment process for a metal, the deposit types to be included in the assessment must be specified. This requires knowledge of the diagnostic characteristics of the existing deposits, as well as expertise to recognize which deposit types could occur within the geologic framework of the areas of interest. If possible, the relevant deposit types should be defined in the start-up meeting of the assessment process. If available, global well-established deposit models should be used in the assessment. Statistical tests should be used to examine if the grade or tonnage distributions of local deposits and occurrences are significantly different from the well-known deposits on which the global model is based. It is critical that the tonnage

and grade reporting criteria and the sampling unit criteria (spatial rules for the areal definition of a deposit) for the local deposits are similar to the criteria used in the global grade-tonnage model. Only if the local deposits differ significantly in size or grade from the existing global grade-tonnage model, or if a global grade-tonnage model for a deposit type does not exist, should a new model be constructed.

The construction of a new grade-tonnage model requires that grade and tonnage data are available for a large enough group of well-explored deposits. Preferably, data from at least 30 deposits should be used for a grade-tonnage model, and 10 deposits is considered as an absolute minimum. The quality of information gathered for a new model must be checked. The resource estimates should cover entire deposits, not only parts of them, and all estimates should be at the same confidence level. If resource data reported according to the present-day industrial standards is absent, data that is based on thorough drilling of the apparently entire deposit might have to be included. Again, spatial rules defining a deposit must be consistently followed. Any new model that is constructed must be included in the assessment report or published separately.

#### **Gathering and compiling exploration information for the metal and deposit types**

Information must be gathered on where exploration for the deposit type under assessment has been performed, what methods were used and how exhaustive this exploration was. The information can be used in the delineation of permissive tracts and in the estimation of the number of undiscovered deposits.

#### **Delineation of permissive tracts for the deposit types**

The delineation of permissive tracts should be done by the expert(s) most familiar with the geology and ore deposits and occurrences of the area. Initial tract boundaries are based on geology and defined so that the probability of deposits of the type delineated occurring outside of the tract is negligible. The tract can be extended to areas where metal deposits or occurrences of the type being assessed, or geochemical or geophysical data indicate the existence of the permissive geological unit under cover thinner than one kilometre. Areas of different degree of information quality should be drawn as separate permissive tracts. After the initial drawing of a tract, exploration information is used to exclude barren areas. Only areas, where very thorough exploration extending to the predefined assessment depth has not revealed any occurrences should be excluded from the tract as barren. The criteria used in the delineation of tract boundaries should be recorded at the time of delineation.

### **Assessment meeting**

The main purpose of an assessment meeting is to estimate the number of undiscovered deposits within each permissive tract. The pre-meeting tasks have to be completed before the assessment meeting and the team members must be familiar with the outcome of the tasks.

The meeting should begin with a brief review of the pre-meeting work. The general characteristics and diagnostic features of the deposit type in question should be reviewed, as well as the general features of the geology of the areas assessed. The suitability of the selected deposit model should be reviewed and the permissive tracts defined by experts before the meeting should be evaluated and accepted or adjusted. Adjustments to any of the previous work can be done in the assessment meeting, but it is preferable to have the possible adjustments and discussion completed already during the pre-meeting phase. Therefore, it is very important to distribute the results of the pre-meeting tasks to the whole assessment team well before the assessment meeting.

After the review part, the number of undiscovered deposits in each permissive tract is estimated. This part of the assessment meeting begins with an introduction of the guidelines and rules used in estimating the number of undiscovered deposits, to make sure all participants understand the estimation process in a similar way and have all the essential information to use in the estimation. Issues to review in the introduction include:

- Possible methods to use as guidelines to make the estimates: frequency of deposits in well-explored areas (deposit density models), local deposit extrapolations, counting and assigning probabilities to anomalies, process constraints, relative frequencies of associated deposit types, area spatial limits, total known amount of metal.
- Spatial rules used in defining a deposit in the models.
- The estimated number of undiscovered deposits must be consistent with the selected grade-tonnage model (half of the deposits must have tonnage greater than the median tonnage of the model, a fourth of the deposits must have tonnage greater than the 75% quantile of the model, and so on).
- Known occurrences and deposits with incomplete resource information are counted as undiscovered in the estimation.

After the introduction, the specialists independently make their own estimates of the number of undiscovered deposits within each permissive tract. The estimates represent the probability that a fixed but unknown number of undiscovered deposits exists within the permissive tracts. The estimates are given at three probability levels: 10%, 50%, and 90%. The number of deposits  $N$  estimated at  $X\%$  probability level indicates the largest number of deposits present with probability  $X\%$  or more; the probability of more than  $N$  deposits is less than  $X\%$ . The estimates can additionally be made at 5% and 1% probability levels, but these should only be used if the estimated numbers at higher probability levels are very low (zero or one). Uncertainty of the estimate is indicated by the spread between the numbers associated with the 90% and 10% probability levels. The expected number of undiscovered deposits at a given probability level can be taken as a measure of the favourability of the existence of the deposit type.

After all experts have made their independent estimates, a general discussion follows. The experts may reconsider and adjust their estimates during the discussion. At least those estimators

with clearly lower or higher than average values should be asked to explain how they reached their estimates. The purpose of the discussion is to reach a consensus on each probability level estimate. The consensus estimate is not necessary, as the estimates of all experts can be input to MapWizard software, which estimates a probability distribution of the number of undiscovered deposits. The individual estimates of the experts and the consensus values (if consensus was reached) are documented, as well as the criteria used by the experts when estimating the number of deposits.

## **1.6. Reporting of results**

Reporting of results is an essential part of the assessment procedure. The tract description documents produced for each permissive tract are an important part of reporting. Mineral deposit type summary documents combine information from all permissive tracts containing deposits of certain type. Metal-specific reports provide summary information of the total estimated undiscovered resources of the metals assessed.

The reports should be based on templates to assure that for each tract, deposit type and metal, all essential information is consistently reported. The templates should contain guidelines and instructions on how they should be filled and what data should be included.

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## 2. Grade-tonnage model data

*Kalevi Rasilainen*

This section gives a short description of grade-tonnage model construction. A grade-tonnage model is an essential component of any quantitative resource assessment carried out according to the three-part method. Even when a published grade-tonnage model is used, it is important to understand the underlying principles according to which the model has been constructed. This understanding becomes crucial when a new model has to be constructed. Such a need might arise, if a global grade-tonnage model does not exist for a specific mineral deposit type, if the existing model is outdated, or if the local deposits are not consistent with the existing model.

### 2.1. Parameters to record

The grade-tonnage model is based on data from well-known deposits. Numerous attributes and properties of a mineral deposit can be recorded, but few are necessary for the construction of a simple grade-tonnage model. However, if data are available and time and resources allow, it is better to record too many than too few parameters. At least the following information should be recorded if available:

- Deposit name
- Country
- Deposit type
- Location (geographic coordinates)
- Surface area
- Total pre-mining ore tonnage in metric tons
- Metal grades in weight percent
- Completeness of resource information (Totally delineated – possibly open – probably open – open)
- Cut-off grade used
- Reporting code used for the resource estimate (JORC, PERC, SAMREC, NI 43-101, CRIRSCO, UNFC). Some resources might be reported using historic or other non-standard code.
- If several deposits have been combined as one
- Complete bibliographic reference to the resource data

## 2.2. Sampling unit

Only well-known deposits that are believed to be totally delineated in three dimensions should be included in the grade-tonnage model. It is very important that all deposits are recorded using the same sampling unit. Mixing data representing different entities like only part(s) of a deposit, a district containing several separate deposits, a deposit that should be combined with another based on the spatial rule, (partial) production data only or resource data only is the most common mistake that causes the generation of biased grade-tonnage models.

## 2.3. Pre-mining resource and reserve data

The grade and tonnage data should represent the total deposit “pre-mining” values. This means past production + present resources (including reserves) at lowest possible cut-off value. The resources are usually reported separately for measured, indicated and inferred classes. If reserves are not included in resources, then proved and probable reserves are also reported. The metal grades for the whole deposit should be calculated by weighting with corresponding class tonnages. The resource and reserve category data should be recorded separately, although the classes are combined into a total resource in the final grade-tonnage model dataset.

## 2.4. Spatial rule

A spatial rule must be applied. Deposits/ore bodies nearer to each other than the spatial rule (critical distance) should be counted as one deposit, and their resources should be combined. The distance is measured from the margin of the orebody or its alteration zone.

## 2.5. Grade information and missing values

Grade information for all metals reported should be initially recorded. Metals to be included in the final model can be decided when all data has been collected. If there are numerous missing grade values for some metals, these metals might have to be excluded from the final model.

Missing grade values should not be confused with reported zero values. In the former case, the value is not known, in the latter it is reported to be zero. If possible, these should be distinguished, although it might be difficult to know which alternative the reported zero value represents.

## 2.6. Common sources of biased models and reasons to review the data

Some common sources of errors that cause biased grade-tonnage model include:

- Mixed geologic environments
- Poorly known geology
- Data recording errors
- Mixed deposit / district data
- Mixed production / resource data
- Incomplete production / resource data
- Mixed mining methods

Signs that indicate the need to review the grade-tonnage data include:

- Deviations from lognormality
- Outliers
- Subgroups
- Standard deviations for logarithmic tonnage values larger than 1.0
- Significant correlation between tonnage and grade
- Bimodal tonnage or grade distribution

### 3. Spatial data for fuzzy logic and weights of evidence computations

*Johanna Torppa*

This section describes the use of various types of spatial data as input to mineral prospectivity modelling tools in the process of delineating and classifying permissive tracts. The scope is limited to two methods, fuzzy logic and weights of evidence, as these are presently implemented in MapWizard software.

#### 3.1. Suitable datasets

Both the fuzzy logic and weights of evidence tools of MapWizard take as input several evidence datasets, each of which represents a quantity that has a relation to the occurrence of the mineral deposit type of interest. Evidence data must be in raster format and all the datasets must be in the same coordinate system and have the same gridding. In addition to evidence data, weights of evidence method requires a set of training points as input. Usually training points are locations of known mineral occurrences in regional scale prospectivity modelling and favourable locations based on drill core data in target scale modelling. Maps representing input rasters and training points for an example region are shown in Figure 3.1.

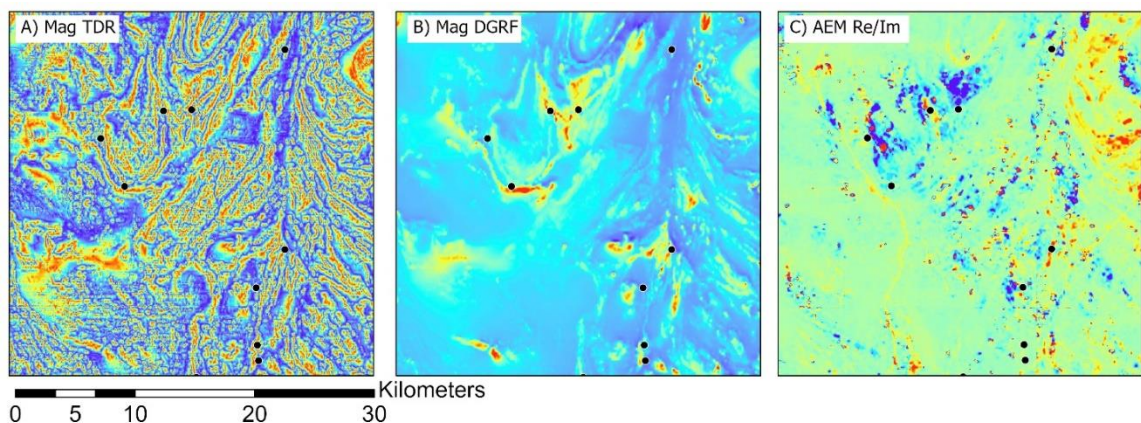


Figure 3.1. Maps of evidence data for an example region with known mineral occurrences (training points) shown as black dots: a) real/imaginary component ratio of the electromagnetic response, b) magnetic anomaly and c) tilt derivative of the magnetic anomaly. Red colour refers to high value and blue to low value of the quantity.

Evidence data applicable for defining the permissiveness or prospectivity of a region consist of measurable and observable quantities that have a relation to the occurrence of mineral deposits and are determined with high enough spatial accuracy. The required spatial accuracy depends on the scale of the spatial features related to the deposits. Commonly used quantities include various geophysical, geochemical and geological properties of the bedrock and the overburden. Preparing data with varying spatial resolution for data integration is a challenging task, and experts on spatial data analysis should perform this operation together with geologists, geophysicists and geochemists.

### Geophysical evidence

Geophysical data describe, either directly or indirectly, the physical properties of the ground. Usually, with geophysical data, we mean indirect measurements from the ground surface, from the air (aircraft/drone) or from a drill hole. Petrophysical data means direct determination of physical properties of rock from a rock sample or from a drill hole.

Airborne geophysical measurements are commonly used as a data source in generating evidence layers for mineral prospectivity modelling. Depending on the spacing of the flight lines, measurement data can be interpolated to grids with point spacing commonly from a few tens to a few hundreds of meters. Measured quantities include, for example, electromagnetic responses from the ground, and Earth's magnetic and gravity fields. Indirect geophysical measurements can be assigned to a single xy location on the ground surface, but they contain information from a volume of rock and overburden around and below this location. Geophysical signals typically attenuate with increasing distance from the source, and the shape and dimensions of the "footprint" volume depend on the physical properties of the surrounding material and on the measurement system. Various data transformations can be computed for many geophysical datasets, and geologists and geophysicists should work in close co-operation to find the most suitable transformations for each prospectivity modelling problem. Figure 3.1 shows examples of geophysical data rasters. Figures 3.2 A and B cover a subregion of Figure 3.1 and show the airborne measurement flight lines and examples of derived geophysical quantities on the background.

Ground-based geophysical measurements can, in principle, be applied as well for generating evidence layers, but commonly the coverage of airborne measurements is more suitable for the purposes of prospectivity modelling. Petrophysical data helps in interpreting the geophysical data, selecting or generating the right features for prospectivity modelling, and generating training points for supervised methods, like weights of evidence.

## Geochemical evidence

Geochemical data is always measured from a sample and it provides information on elemental or mineralogical composition of the sample material. Collecting samples for geochemical data is tedious and the spatial resolution of geochemical information is often much poorer than that of geophysics, which can be collected using airborne instruments. In addition, laboratory analysis of the samples is expensive, which also restricts the amount of available geochemical data.

However, since elemental and mineralogical information is highly important considering mineral prospectivity, geochemistry is used in prospectivity modelling in different ways. Sometimes it is useful to interpolate geochemical data from the study area, even though the spacing of interpolation grid points would be large compared to the footprint of the deposit. Instead of interpolation, also distances to sampling points with anomalously high and/or low concentration can be computed, and values descriptive of favourability can be computed from the distance values. Since drilling is expensive and time consuming, most of the geochemical data is collected from the overburden or plants. The processes that bring molecules and ions up from the bedrock are complicated which has to be taken into account when using soil and plant geochemistry in mineral prospectivity modelling. The compositional nature of geochemical data also brings challenges when combining concentration information from different elements.

Figures 3.2 C and D show an example of spatial resolution of geochemical sampling points, and the corresponding interpolated concentration values. It is easy to see, that the geochemical data is highly undersampled, and the frequency of spatial variation of the corresponding interpolated values is unrealistically low, and most likely will not point out individual deposits. Of course, there might be sites where geochemical sampling has been carried out with a dense enough grid, but often, compared to geophysics, the resolution is very low, and combining geochemistry with geophysics must be carried out with care.



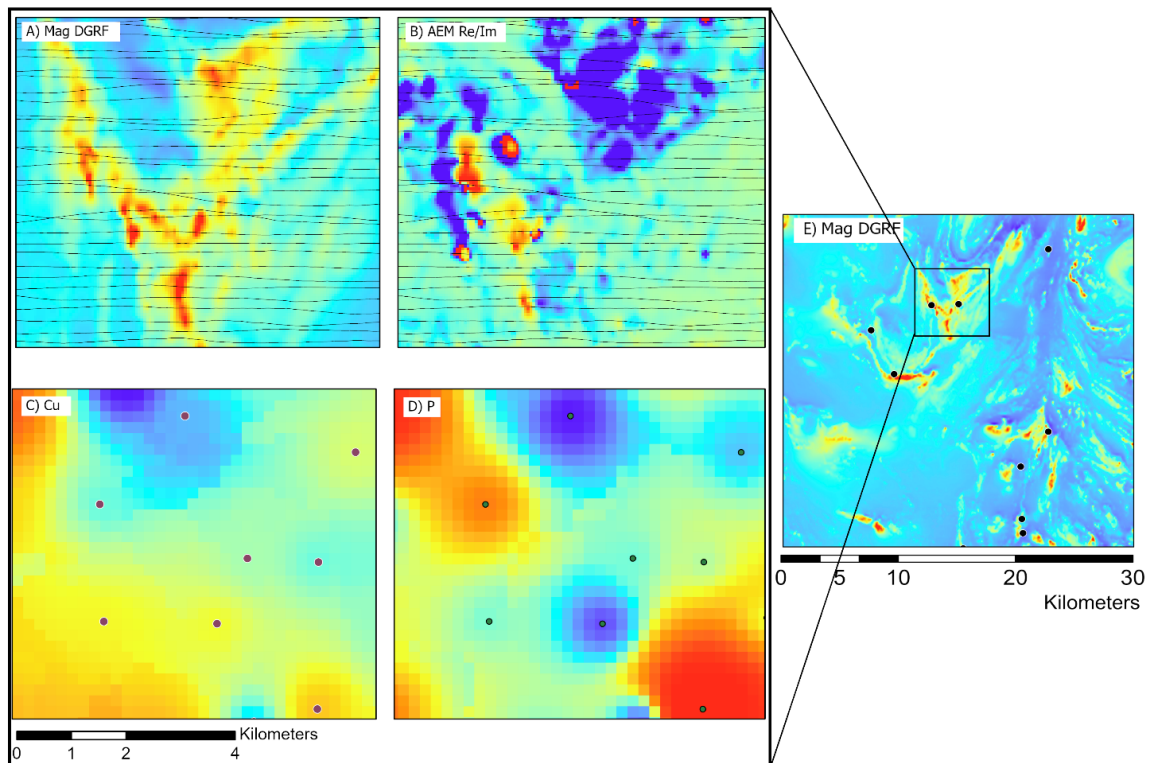


Figure 3.2. Raster representations of interpolated grids from airborne geophysical measurements and till sample geochemistry for a 6 km x 6 km subregion of the Figure 3.1 rasters. Figures A and B: flight lines on top of the corresponding rasters (cell size 50 m x 50 m) for the magnetic anomaly and real/imaginary component ratio of the electromagnetic response, respectively. Figures C and D: geochemical sampling points on top of concentration values (raster cell size 200 m x 200 m) for two chemical elements.

## Geological evidence

Geological models and expert interpretations are sometimes used in prospectivity modelling, although they differ in character from the geochemical and geophysical data, which is directly derived from measured quantities. Commonly used geological data include location of structures, boundaries of lithological units, and rock-type information of drill core and outcrop samples. Geological data can be transformed to evidence data in many ways, and the most suitable approach depends on the mineral deposit type that is to be modelled.

In Figure 3.3, four examples of geological evidence maps are shown. Rock type information can be used, for instance, in form of weighted distances to sampling points with favourable rock types and to those with not favourable rock types (Figure 3.3A). Metamorphic grade sometimes correlates with the existence of deposits and can be regarded as ordinal categorical data (Figure 3.3B). Structural information is often expressed as the distance to the structures (Figure 3.3C) or

as the density of the structures. Lithological units are categorical in nature and should be considered as nominal classes (Figure 3.3D), unless there is strong evidence of one lithology being more favourable for the existence of the deposits than the other.

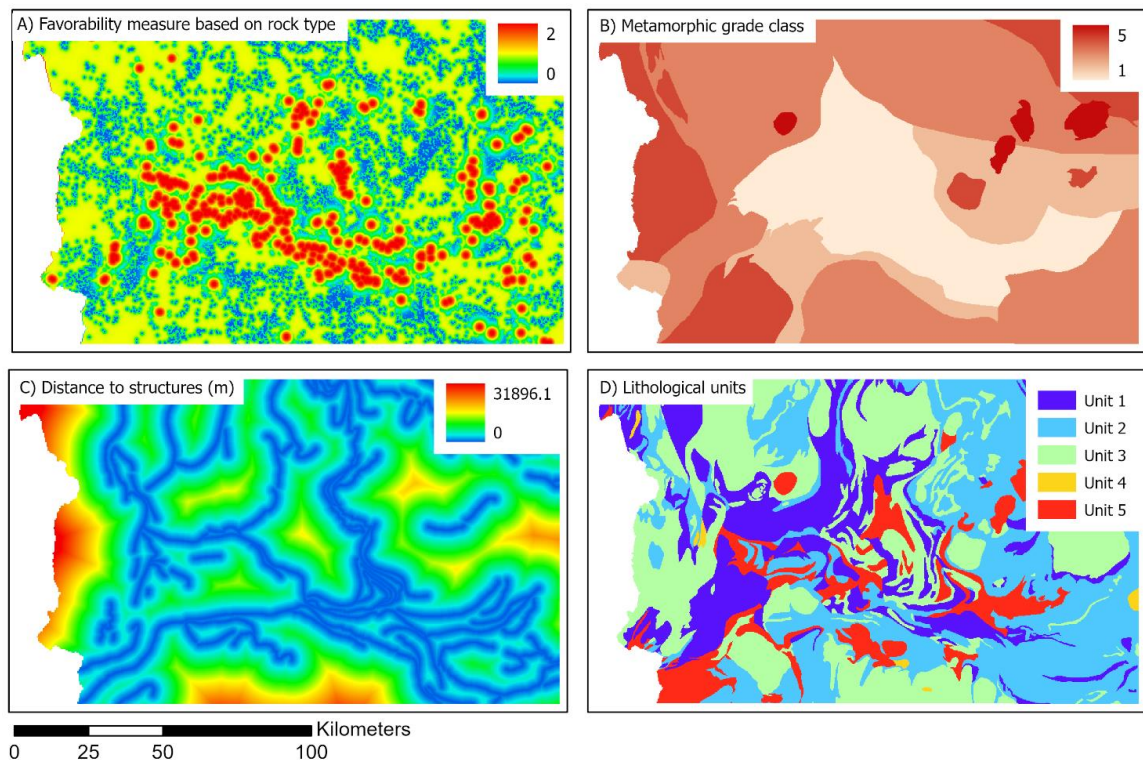


Figure 3.3. Examples of derivatives from geological data. A) Distance-based favourability measure based on drill-core and outcrop sample rock type, B) metamorphic grade as ordinal classes, C) distance to structures in meters and D) lithological units as nominal classes.

### 3.2. Pre-processing of the data for MapWizard fuzzy logic and weights of evidence tools

#### Fuzzy logic

Map Wizard's Fuzzy logic tool takes so called evidence membership rasters as input. Membership represents the favourability for the deposit of interest to occur based on one specific geoscientific parameter. Often the range [0,1] is used for the value of the membership, zero referring to not favourable at all and 1 to totally favourable. For example, if we have an interpolated gravity anomaly map (Figure 3.4 A), and we know that low gravity anomaly values occur at the deposit sites, we transform the gravity data so, that the low gravity values get membership values close to 1 and the high gravity values get membership values close to 0. This

transformation can be linear, logistic, or any other suitable monotonically decreasing function. In Figures 3.4 B and C, we show examples using a function that can be used to emphasize large membership at a range of small values. If our evidence responds to the occurrence of deposits with large values, we use a monotonically increasing function to transform the evidence values to membership values. If favourability is high around a certain evidence data value and smaller at both high and low values, one can use the Gaussian function (Figure 3.4 D) for membership transformation. In principle, one can use any function that describes the relation between the occurrence of deposits and evidence feature value.

Sometimes memberships are defined for discretized evidence values or categorical evidence classes, such as lithological units. In that case a transformation function is not necessarily needed, if the expert is able to estimate the membership value for each class.

The memberships do not always have to cover the entire range of totally non-favourable (0) to totally favourable (1), but it depends on the strength of the evidence:

1. If the relation of your evidence feature to the occurrence of deposits in the study area is strong, you can use the entire range [0,1]
2. If the indication of high favourability is strong, but the non-favourable regions are not well represented, use a larger minimum value, for instance [0.2,1]
3. If the indication for non-favourability is strong, but the regions of high favourability are not well represented, use a smaller maximum value, for instance [0,0.8]
4. If neither high or low favourability are well represented, but the relation of the evidence feature to the occurrence of deposits is only slight or vague, suppress the range from both ends, for instance [0.2,0.8]

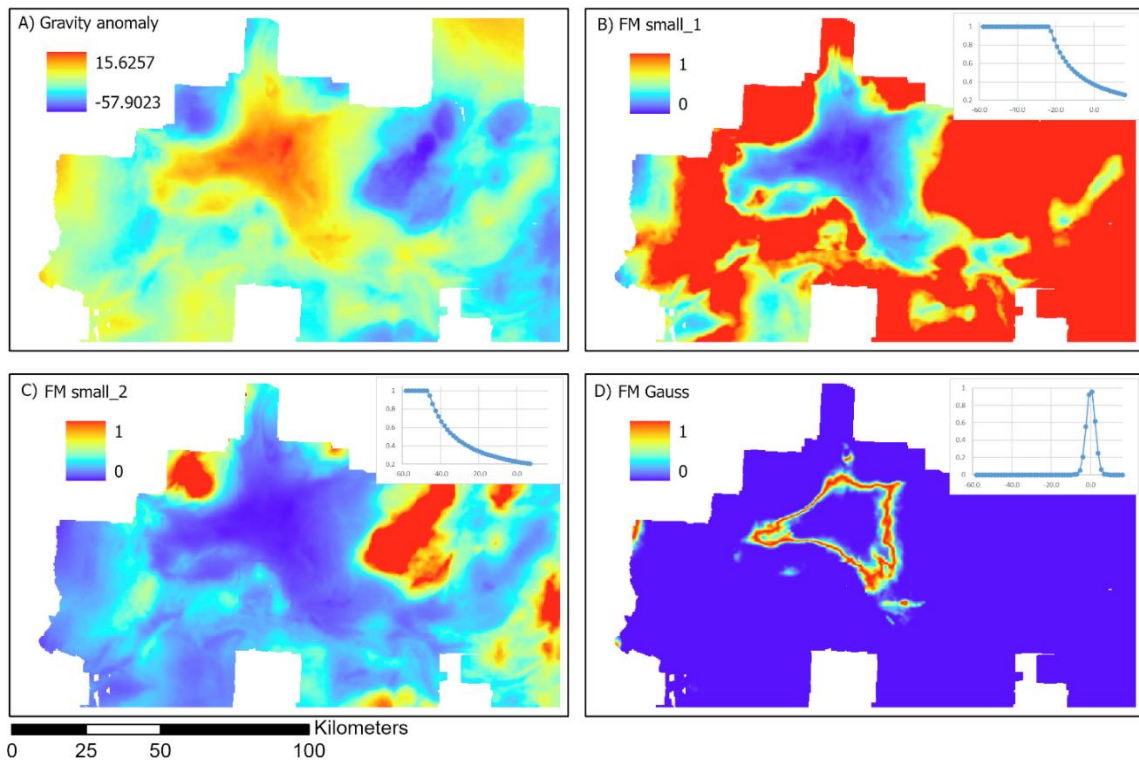


Figure 3.4. Examples of membership maps for a gravity anomaly map (A). Images B and C show two different examples for a decreasing membership transformation function. Image D shows memberships obtained using a Gaussian function.

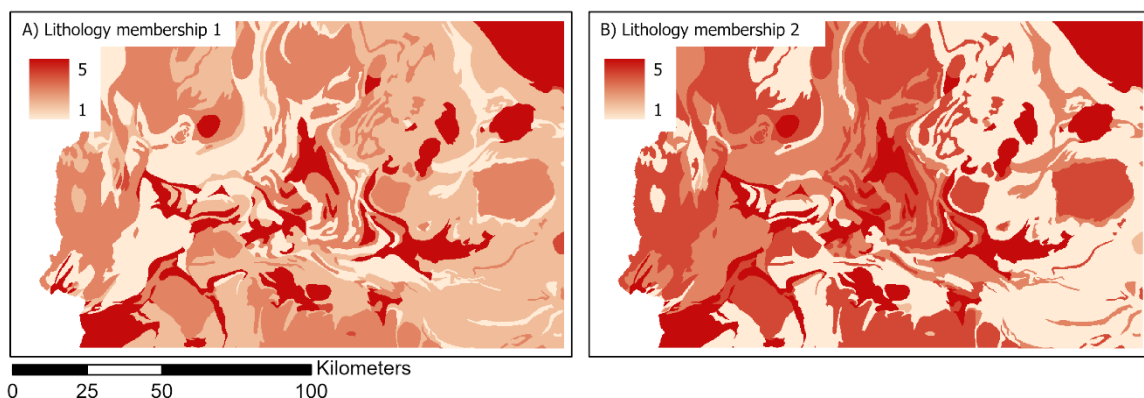


Figure 3.5. Examples of two different membership classifications for the lithology in Figure 3.3 D.

### Means for computing continuous membership values

To generate a raster representing continuous membership values, a membership transformation function must be defined. Using, for instance, R or Python, it is possible to apply any function for the transformation. The transformation function can be defined computationally using the locations of known deposits or alternatively expert knowledge. If coding is not an option, GIS

software, such as ArcGIS and QGIS, offer a raster calculator tool, where use can input the transformation function.

ArcGIS and QGIS also provide a few built-in functions for membership computation, but neither of these GIS software provides the possibility to adjust the range of the membership values; they always range from 0 to 1. You can manually transform the memberships from range [0,1] to a custom range [your\_min,your\_max] using the Raster calculator tool with the function

$$\text{rasterval\_mod} = \text{rasterval} * (\text{your\_max} - \text{your\_min}) + \text{your\_min}$$

### **Means for defining discretized membership values**

For defining membership values for discretized or categorical data, the form of the transformation function does not have to be known, but the membership values can be manually provided for each class. However, if the evidence values are ordinal, also a transformation function can be used. As in the case of continuous evidence and membership values, assigning the membership values manually for discretized or categorical data can be done by coding or using GIS software.

## **Weights of evidence**

MapWizard's Weights of evidence tool takes three different datasets as input: evidence data, training data and study area mask.

Evidence rasters should be classified and of integer type. Depending on the choice of the type of the weights computation, the order of values matter (Ascending and Descending type) or does not matter (Categorical type). Figure 3.6 shows two example classifications of gravity data shown in Figure 3.4 A. The data have been classified in nine classes, and in Figure 3.6 A the classification is done using equal intervals of gravity value, while in Figure 3.4 B class division is determined by having an equal number of pixels in each class. The classification scheme affects the result of WofE computation. The number of classes should be large enough to reveal the correct threshold for binary classification in ascending and descending weights computation. For categorical weights computation, an optimal number of clusters reveals differences between the occurrence of training points on different classes; it must be neither too small nor too large. Data can be classified using R or Python or, if coding is not an option, GIS software such as ArcGIS and QGIS.

Training data for weights of evidence is a set of known occurrences of the modelled mineral deposit type. There is no lower limit for the number of deposits, but the larger the better. Some tens is good but a hundred is much better. Training points are given to the tool as a point feature shape file (.shp)



The input parameter “mask” is optional and can be used to restrict the weights of evidence analysis to a certain subregion of the input dataset.

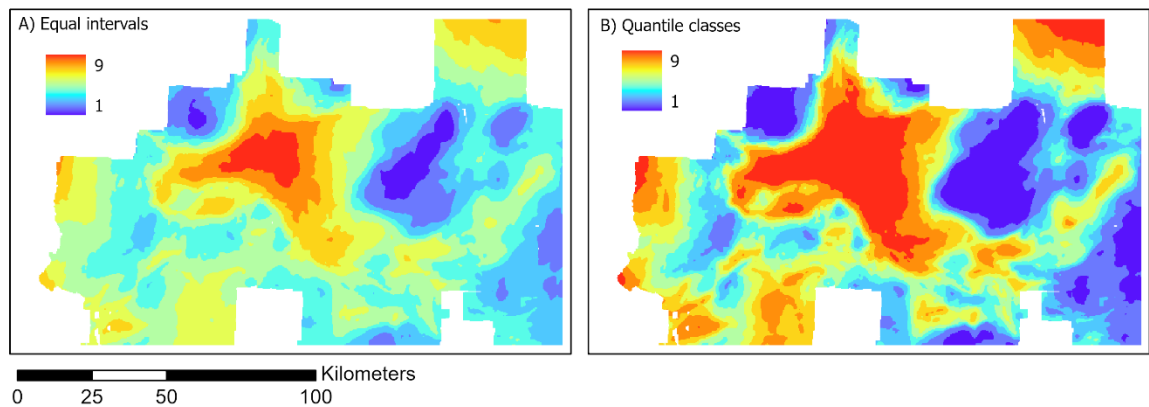


Figure 3.6. Two different classification methods for the gravity data in Figure 3.4 A.

## 4. Tract delineation process

*Kalevi Rasilainen*

A recommended process for the use of mineral prospectivity modelling techniques in the delineation of permissive tracts is presented in this section. The process is based on GTK experience of using the fuzzy logic method in the Vihanti-Pyhäsalmi area in Finland.

### 4.1. Introduction

The purpose of the test was to compare permissive tracts delineated by mineral prospectivity modelling techniques to the tracts delineated previously by experts. Expert assessment of undiscovered VMS resources in Finland was carried out in 2014. The Vihanti-Pyhäsalmi area (Fig. 4.1) was selected as the study area for the MapWizard study because it is a well-known VMS area that contains several VMS deposits and occurrences and has a long history of exploration and research.

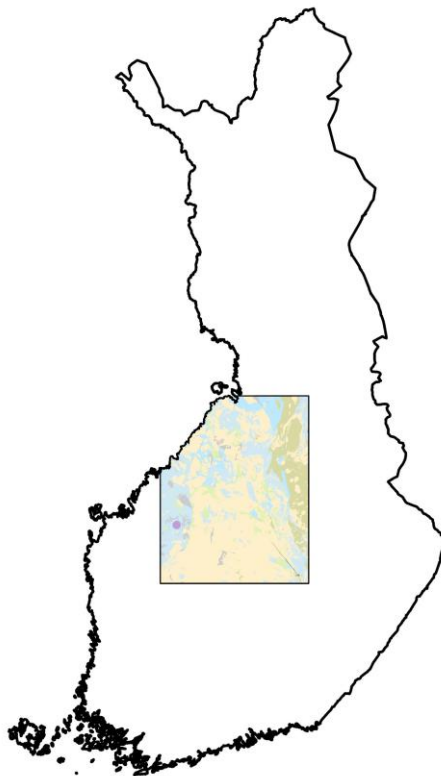


Figure 4.1. Location of the Vihanti-Pyhäsalmi study area.

## 4.2. Experts tracts and VMS occurrences

Four permissive tracts for VMS were delineated in the Vihanti-Pyhäsalmi study area by experts in 2014. Eleven VMS deposits and 42 occurrences exist in these tracts. The Vihanti and Pyhäsalmi tracts contain felsic-type VMS deposits, and the Rauhala and Upper Svecofennian tracts contain VMS deposits that belong to the bimodal-mafic type (Fig. 4.2).

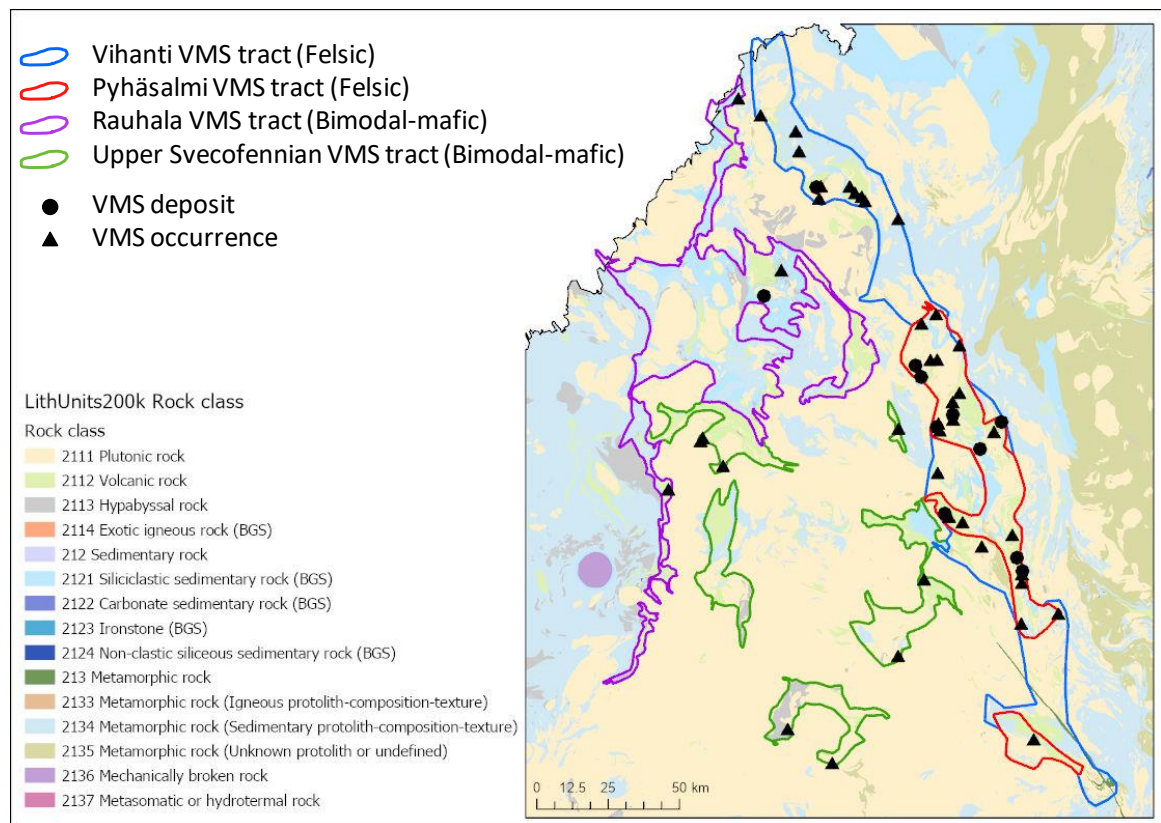


Figure 4.2. Expert-delineated permissive tracts and known VMS deposits and occurrences in the Vihanti-Pyhäsalmi area.

In the expert assessment, rock units permissive for VMS deposits were selected using interpreted tectonic setting. Only units related to a Palaeoproterozoic magmatic arc environment were accepted, all other units were excluded. Figure 4.3 shows the tectonic setting classification of the Vihanti-Pyhäsalmi area.



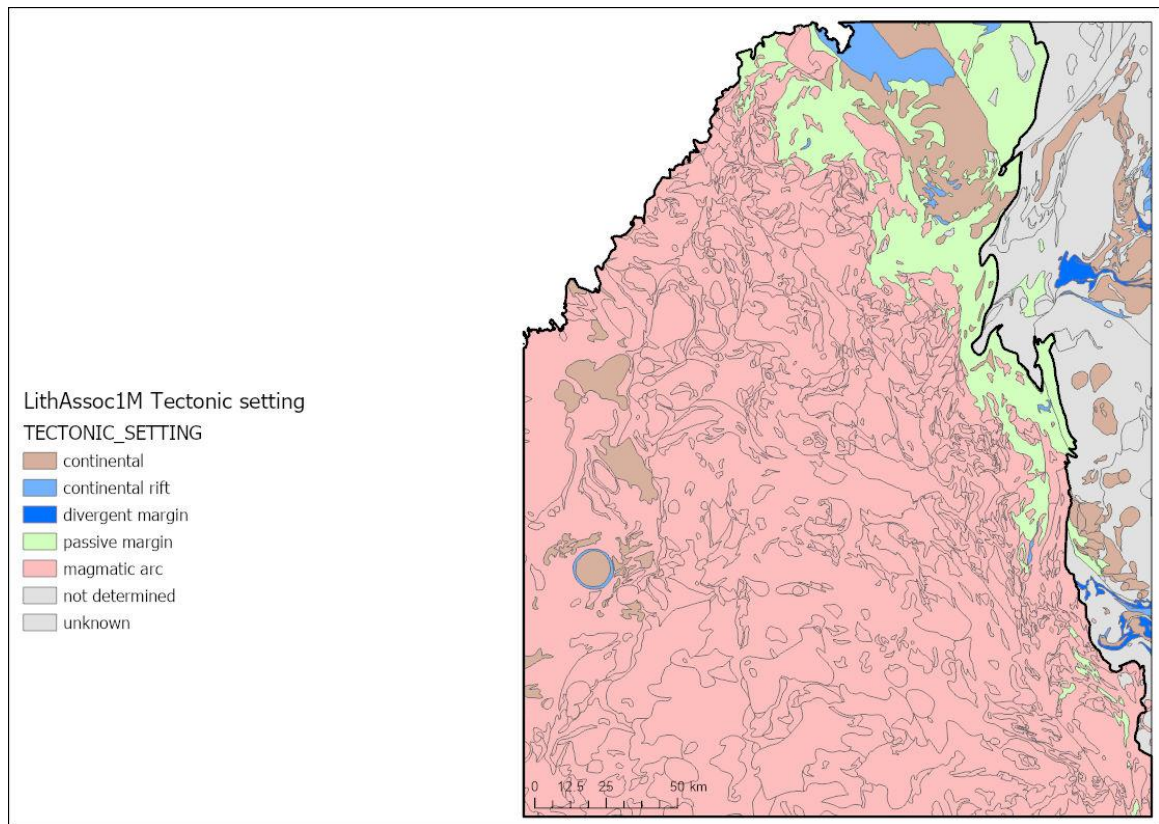


Figure 4.3. Tectonic setting of the lithological units within the Vihanti-Pyhäsalmi area.

Lithologic units representing continental, continental rift, divergent margin and passive margin setting were excluded in the first stage. Only rocks with a magmatic arc setting were included. Next, middle continental crust rocks and ocean floor sedimentary rocks of magmatic arc affinity were excluded. Figure 4.4 shows the remaining permissive lithological units after the non-permissive units had been excluded. The permissive tracts delineated by experts based on the permissive lithological units are also shown. All the known VMS deposit and all but a few occurrences occur within the permissive rock units. The tracts are extended outside of the permissive rock units based on the existence of VMS occurrences and the knowledge that the Vihanti and Pyhäsalmi group permissive volcanic rocks occur below the surface. The volcanic rocks of the bimodal-felsic Vihanti and Pyhäsalmi tracts are 1.92–1.93 Ga low-K basalts, basaltic andesites and rhyolites with volcanic arc affinity. These tracts host 10 known VMS deposits and 31 occurrences. The volcanic rocks of the bimodal-mafic Rauhala and Upper Svecofennian tracts are slightly younger 1.85–1.89 Ga calc-alkaline basalts to potassium rhyolites with island arc affinity. These tracts host only one known VMS deposit and 11 occurrences.

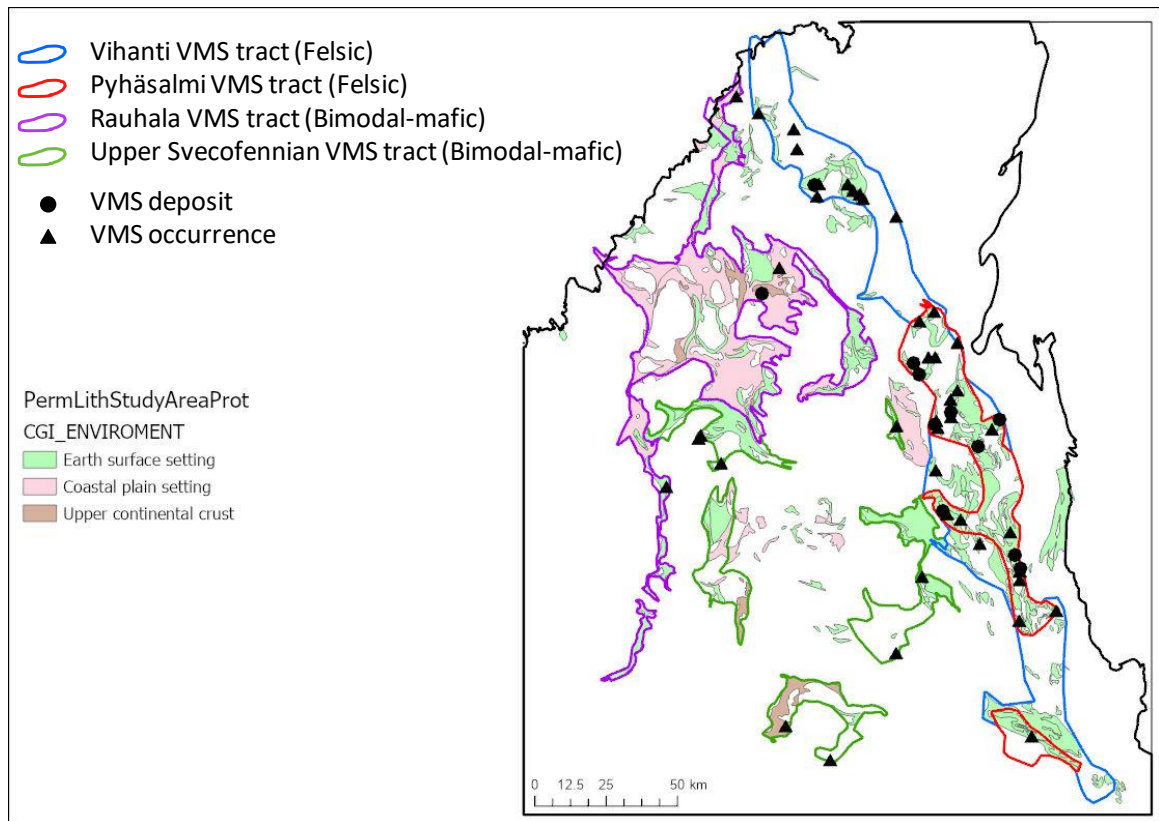


Figure 4.4. The permissive lithological units, known VMS deposits and occurrences and expert-delineated permissive tracts.

### 4.3. Fuzzy logic delineation of permissive tracts

Data available for the fuzzy logic process included areal gravity and low-altitude airborne magnetic and electromagnetic data. Till geochemistry does not reflect the underlying bedrock with required accuracy in the Vihanti-Pyhäsalmi area, and it could not be used. Structural data was not used as all faults and shears in the area are interpreted to be younger than VMS mineralisation. Figure 4.5 shows the available evidence layers for fuzzy logic analysis. The fuzzy membership values are based on the number of known deposits and occurrences within each raster value class. This suggests that the evidence layers can be considered to measure prospectivity for VMS mineralisation in the area.

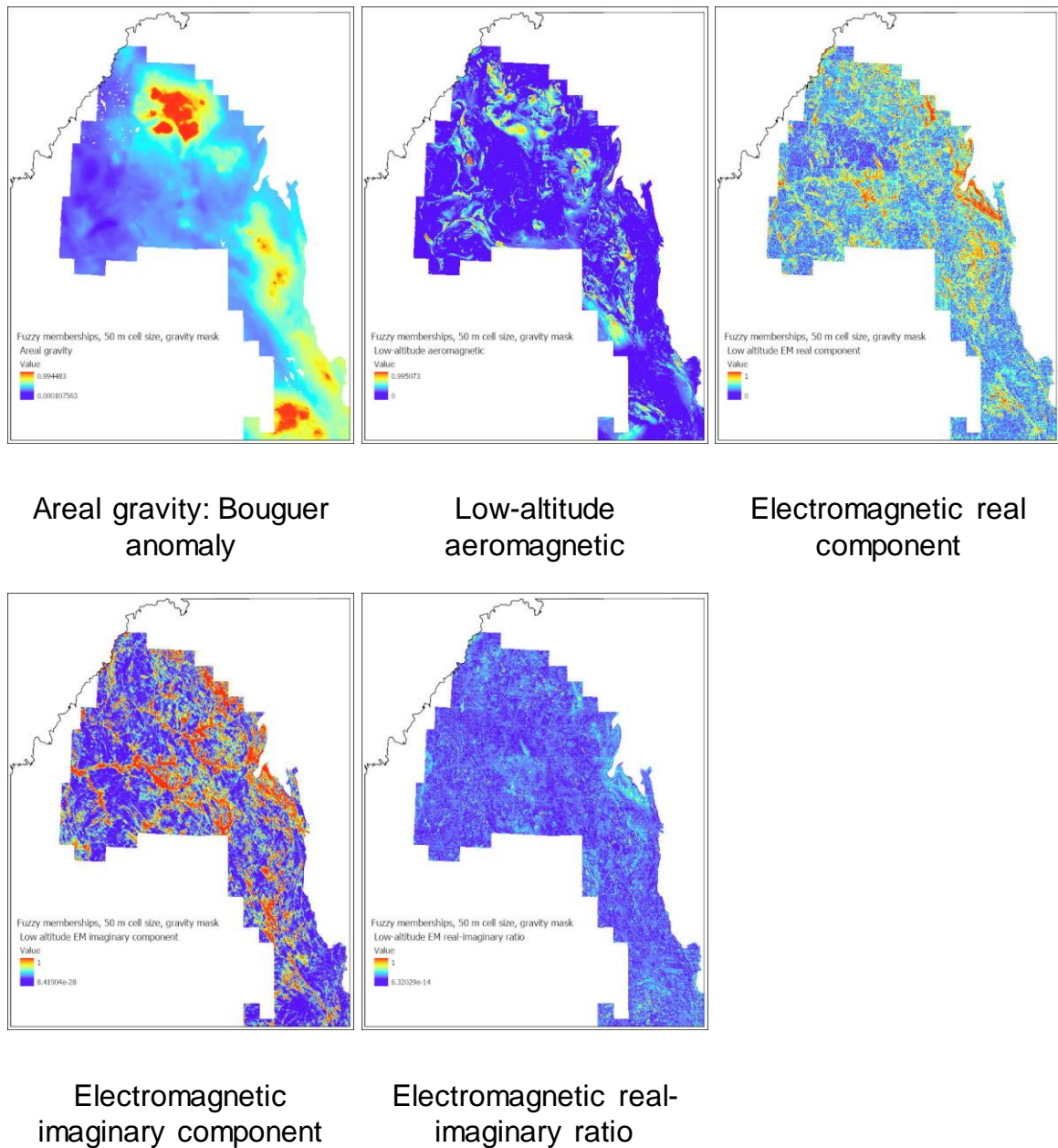


Figure 4.5. Evidence layers for fuzzy logic.

Several combinations of layers were tested to see which combination produces tracts most similar to the expert tracts. Figure 4.6 shows the combination of gravity and magnetic data using the fuzzy OR operator. There is a broad correspondence between the fuzzy overlay raster high values and the location of known deposits and occurrences within the bimodal-felsic Vihanti and Pyhäsalmi tracts. This is not surprising, as these two tracts contain the majority of the known deposits and occurrences that were used in defining the fuzzy membership values of the input rasters.

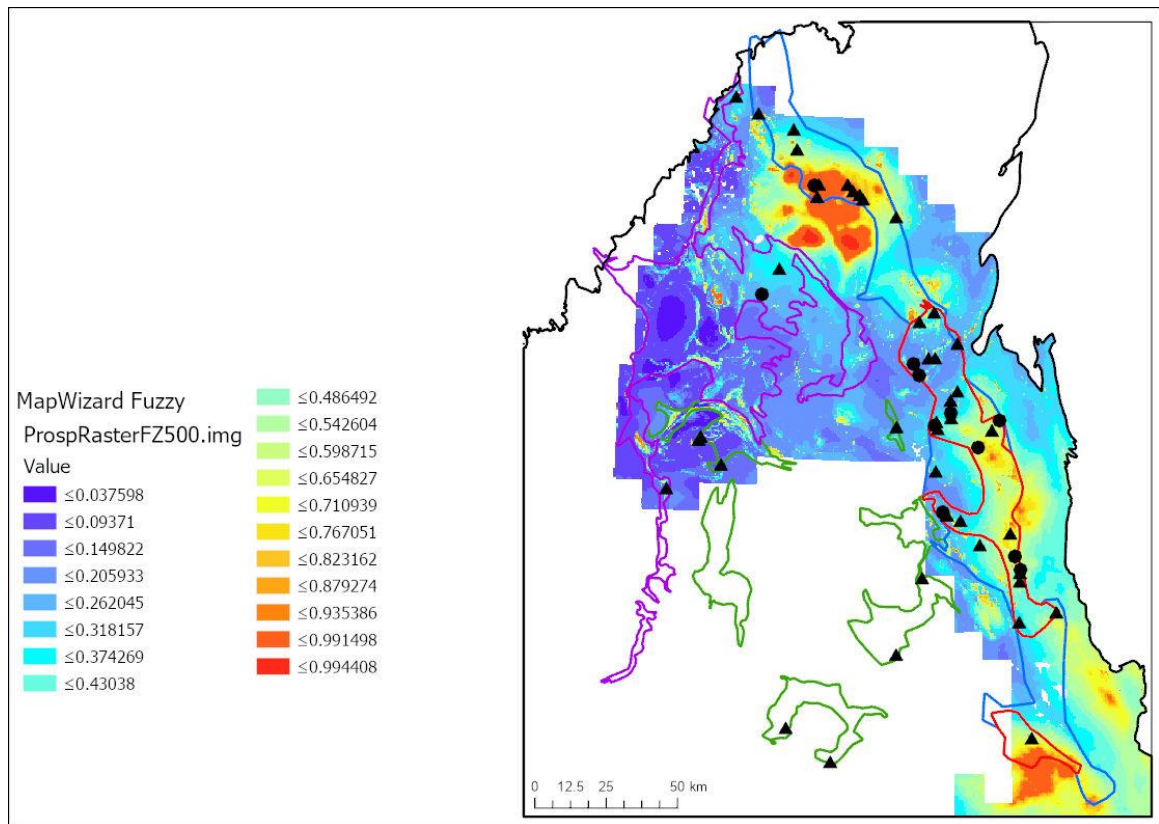


Figure 4.6. Fuzzy overlay raster combining gravity and magnetic data using the OR operator.

Several raster values were tested as tract boundary values. Figure 4.7 shows a raster in which values smaller than 0.25 are excluded. This raster was taken to represent a proto tract. Further modification was needed to remove the small isolated parts so that only the large continuous areas remained.



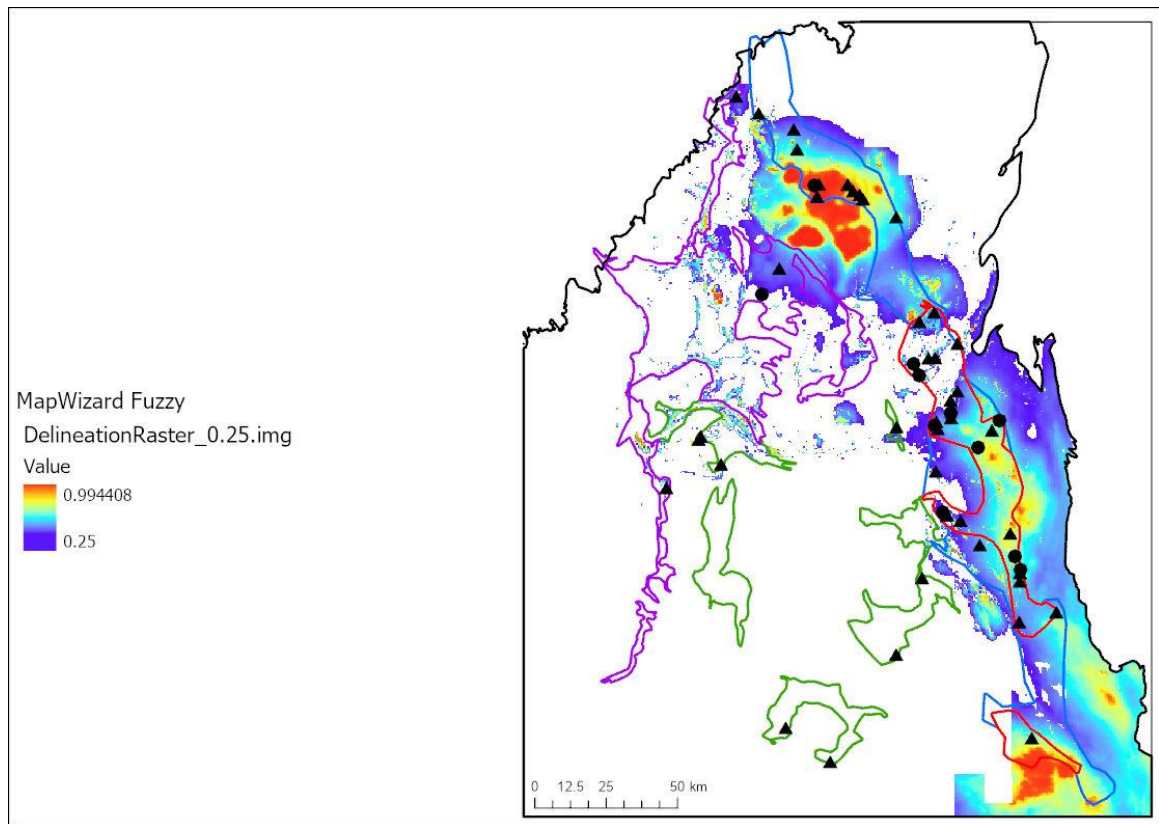


Figure 4.7. The fuzzy overlay raster of Fig. 4.6 with values less than 0.25 excluded.

#### 4.4. Suggested delineation process using mineral prospectivity modelling techniques

The results from GTK tests indicate that delineation of permissive tracts using criteria that measure prospectivity might cause problems. The term “permissive tract” means an area where geology permits or allows the existence of deposits. On the other hand, “prospectivity” or “potential” might be taken to indicate something more than just permissiveness. There are only two levels of “permissive” (yes, no) but there can be a number of levels of “prospective” (very low, low, medium, high, very high). A permissive tract does not have to contain any deposits, it is sufficient that deposits could exist. In prospectivity modelling, the goal is to find areas as prospective as possible, and the areas containing deposits are used as training areas. If the evidence layers used in the delineation process measure prospectivity, the question is: what prospectivity value could be used as the outer limit of a permissive tract? This remains a subjective decision to be made by the assessment team.

Based on the above, the following approach is recommended for the delineation of permissive tracts:

1. Define the main controls for the mineral deposit type and hence the permissive tracts (lithological, structural, ...)
2. Define the mappable proxies for these controls.
3. Use a geological map and other available information to delineate permissive areas based on these proxies.
4. Use mineral prospectivity modelling techniques to modify the delineated tract. For example, geophysical data might reveal the continuance of permissive units under cover. If possible, select evidence layer data that measures permissiveness instead of prospectivity. Knowledge-driven methods might be better suited to define tract boundaries than data-driven methods.
5. Use mineral prospectivity modelling techniques to classify the delineated permissive tract based on prospectivity. Use evidence layer data that is related to mineralisation and measures prospectivity. If enough known mineral occurrences exist to be used as training data, data-driven methods might be more suitable than knowledge-driven in tract classification.

The effectiveness of mineral prospectivity mapping techniques in the delineation of permissive tracts depends on the nature of the factors controlling the existence of mineral deposits and the quality and quantity of data that can be used to construct evidence layers and training sets. Nevertheless, using mineral prospectivity modelling techniques in the process of tract delineation and classification can lead in better defined tracts with more internal detail.