Geophysical signatures of mineral deposit types in Finland
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GEOPHYSICAL SIGNATURES OF MINERAL DEPOSIT TYPES – SYNOPSIS

by

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GENERAL ISSUES

A mineral deposit, as an anomalous unit of metalliferous minerals, contains minerals with quite different physical properties to those of country rocks. Pyrite, pyrrhotite or magnetite are common minerals in ore deposits, all of which have distinctive physical properties and may greatly affect the geophysical response. In addition to petrophysically relevant ore minerals, other geological or geometrical factors or environmental conditions influence the geophysical expressions of ore deposits or mineralized systems. The main factors are gathered below. This list is inspired by a summary of the geochemical expressions of ore deposit types presented by McQueen (2005):

1. Composition of the ore deposit and the contained elements.
   - Density depends on the elementary composition of minerals; many metals have high specific densities.
   - Magnetically, the most distinctive are the ferrimagnetic minerals magnetite and the monoclinic form of pyrrhotite.
   - All metals are electrically conductive in a broad sense, but the conductivity of an ore deposit primarily lies with sulphides or graphite.
   - The radioactivity of rocks is based on radioactive elements, mainly potassium (K), uranium (U) and thorium (Th).
2. Form of an ore deposit (e.g., size, shape, orientation, depth; ore mineral distribution and texture).
   - The size, orientation and depth extent of a mineral deposit are the main factors with regard to geophysical expressions.
   - A great depth suppresses geophysical signatures.
   - Gravity and magnetic methods only detect lateral contrasts in density or magnetization, but in contrast, electrical and seismic methods can detect vertical, as well as lateral, contrasts of resistivity and velocity or reflectivity.
   - In the case of sulphide mineralization, the shape of the deposit may affect the magnetic signature by strengthening the remanent magnetization in the direction of the long axis of the deposit.
   - The electrical conductivity of a rock is a function of many factors, among which the mineral texture (galvanic structure) and porosity (with contained water) have a significant role.
3. Associated geological structures.
   - Most of the mineral deposits are structurally controlled; mineral occurrences are often restricted to structural elements such as faults, shear zones and lithological unconformities; some deposits form stratiform bodies, while

others are formed in a specific stratigraphic interval as a stratabound formation.
- Knowledge of the structure interrelationship and stratigraphic units is essential for mineral exploration. Seismic methods are able to produce high-resolution images of the geological structure.

4. Associated host rocks.
   - The association of particular ore types with particular host rock assemblages broadly reflects the geological environment and processes that have formed the ore, e.g. metamorphosed graphitic shales (black schists) in Finland are distributed along all major crustal boundaries. As sensitive and highly reactive, reducing rocks, they may host or be associated with mineralization, and their geophysical properties related to chemical composition can be used as indicators of the geological settings in which they formed (Airo & Loukola-Ruskeeniemi 2004).
   - Mineralization tends to accumulate along plate boundaries. The composition of sedimentary rocks along these boundaries may reveal information on the crustal conditions and processes at the time of mineralization.
5. Non-ore element component.
   - Sometimes, chemical alteration of host rocks produces detectable geophysical signatures if it produces minerals having anomalous physical properties. Although the petrophysical properties of different host rocks or ore deposits may be well studied, there is a lack of information on how the physical properties are related, for instance, to proportional alteration of various kinds.
   - Extensive fluid-related alteration of the host rocks may have a significant effect on geophysical signatures: sulphidization or pyritization (electrical properties), sericitization (potassium radiation), chloritization, carbonate alteration or tourmalinization (e.g. magnetic properties).
   - Mineralogical changes associated with the formation or emplacement of mineralization (such as hydrothermal alteration haloes). In regional geophysics, the expressions of alteration haloes may be minor, but the detailed study of radiometric or hyperspectral analyses permits the mapping of key minerals. If highlighted by more detailed investigations, these haloes may also be recognized by high-resolution airborne surveys.

Regional geophysical data sets

Airborne geophysical data sets provide full coverage of Finland and form the basic material for regional investigations, particularly greenfield exploration. The use of regional data sets in an automated approach to characterizing areas containing known deposits and seeking similar areas elsewhere, or similarity analysis of certain geophysical key signatures, benefits from high-resolution, multivariate geophysical datasets. Concerning more detailed investigations, airborne geophysical data also can motivate applications that require improved spatial resolution and accurate positioning. The integration of different geophysical data sets is a current theme in geophysical and geological interpretation, and there are now more software tools available to facilitate this. However, as stated by Thomson et al. (2007), although image analysis may often seem intuitive, simple image-based assessments of data are not a substitute for proper geologically supported interpretation.

Specifications and general uses of geophysical methods are outlined in the following. The airborne geophysical concept of GTK has been described in detail by Hautaniemi et al. (2005).

Airborne magnetics

The magnetic method utilizes small variations in magnetic mineralogy among rocks (magnetic iron and iron-titanium oxide minerals, including magnetite, titanomagnetite, titanomaghemite and titanohematite, and some iron sulphide minerals, including pyrrhotite and greigite). Magnetic rocks contain various combinations of induced and remanent magnetization, depending on the Earth's primary field. The magnitudes of both induced and remanent magnetization depend on the quantity, composition and size of magnetic-mineral grains. The magnetic method gives a coherent picture of the distribution of magnetization of the crust and is not disturbed by lakes, waterways or soils that may cover the bedrock. In Finland, exposed bedrock hardly makes up more than 3% of the surface. The aim of the magnetic method is to detect

magnetically anomalous source bodies, but also to determine structural trends. Detailed magnetic investigations on magnetic mineralogy complement the regional picture of magnetic anomaly source rocks. Studies on remanent magnetization and the anisotropy of magnetic susceptibility (AMS) are gaining increasing interest as a mineral exploration tool (Willliams 2009). Palaeomagnetic studies may be important for the timing of the mineralizing fluids or the alteration. Discussion of the magnetic mineralogy responsible for magnetization effects is presented in this Special Paper volume in the chapter on Au deposits in southern Finland by Mertanen & Karell (*p. 89*).

Airborne radiometrics

Gamma-ray methods identify the presence of the natural radioelements potassium (K), uranium (U), and thorium (Th) in rocks. Gamma ray penetration is only of the order of half a metre, so that in regions with poor exposure due to glacial, largely transported overburden, the measurement of natural radioactivity due to K, U and Th may not be very useful. In Finland, the use of radiometrics is frequently limited by the wide coverage of glacial soil, with a thickness varying from 0 to 100 m and an average of <10 m. In southern Finland, cultivated land dominates the variation in radiation observed on radiometric maps. Locally, however, gamma-ray spectrometry can be effective in geological mapping and targeting mineralization. The results depend on several factors, including whether (1) there are measurable differences in the radioactive element distributions that can be related to differences in host rock lithologies, (2) the K content of the rock has been modified by alteration processes, and (3) mineralization and alteration have affected surface rocks. Mobilization of individual radioelements in response to specific geochemical conditions makes radioelement ratios sensitive in locating areas of mineralization (Thomas et al. 2000, cited in Morgan 2012). An example of this is the elevated potassium radiation associated with ultramafic rocks in Finnish Lapland (in *Insert 12*). In uranium exploration, gamma-ray methods may provide a means of direct detection. Good results from the use of airborne radiometric data for targeting promising areas for U-Au and U occurrences are reviewed in this volume by Lauri & Turunen (*p. 107*), who discuss the use of airborne radiometric data as a uranium exploration tool in southern Lapland.

Airborne electromagnetics

Airborne electromagnetic (EM) methods are used to screen large areas and provide information for targeting ground surveys. They are capable of directly detecting conductive base-metal deposits. The traditional application of EM methods in mineral exploration has been in the search for low-resistivity (high-conductivity) massive sulphide deposits. The wide whole-country coverage of frequency-domain EM data in Finland is unique in the world and allows mapping of the regional distribution of bedrock conductivity, also supporting structural interpretation. GTK used a fixed-wing multi-frequency survey system that is better suited to relatively near surface applications than deeper investigations (down to 100 m). Electromagnetic survey data are vulnerable to non-geological noise, but also to conductivity anomalies due to soil properties and moisture. The noise is worth filtering out in the case of mineral exploration. The interpretation of electromagnetic data may be demanding, and 3D interpretation methods would greatly strengthen the use of the airborne electromagnetic method. An example of 3D EM modelling by Suppala (*p. 71*) utilizes the effectiveness of frequency-domain electromagnetic data to discriminate magnetite-bearing source rocks and to evaluate the type of magnetism associated with an ultramafic intrusion (Kellojärvi in eastern Finland).

Regional ground gravity data

A high density is the most anomalous physical property of almost every ore mineral. Regional gravity data reveal the density contrasts and can be used to outline geological structures controlling mineralization. Qualitative interpretation of structural features from gravity data is benefitted by the same types of processing methods as used for magnetic data, e.g. horizontal gradients, vertical or tilt derivatives, filtering or upward continuation. Exploration has for long been the primary target of regional gravity measurements in Finland. Gravity surveys have been focused on the most important mineral provinces, such as the Central Finnish Lapland gold province, the Raahe-Ladoga zone and parts of the Häme belt in southern Finland.

Major tectonic provinces, crustal weakness zones and province boundaries have been described using these data (Elo 1997, Elo 2003). A country-wide Bouguer anomaly map has been prepared based on gravity data, provided by the Finnish Geodetic Institute (Kääriäinen & Mäkinen 1997).

Airborne gravity gradiometry

Airborne gravity surveys for GTK have been conducted in three areas: Hammaslahti and Pori (in 2009) and Savukoski (in 2011). In principle, gravity gradiometer systems are more sensitive to shorter spatial wavelengths than sensors that attempt to measure the total gravitational acceleration. For comparable sensitivities to that of an airborne gravity system, this system on a fixed wing aircraft can be used to map features typified by half-wave distances of 200 m. This corresponds to an order of magnitude better spatial resolution than achieved from total field systems at short wavelengths.

Remote / close-range sensing

Remote sensing based on visible to thermal wavelengths (0.3–14000 microns) of reflected and emitted electromagnetic radiation is widely used to scan targets of mineral exploration and mining to obtain information on the mineral composition, vegetation, environment, and the geological structure. The detailed wavelength samples, bands, and spatial resolutions are selected according to their ability to detect specific minerals or vegetation/environmental anomalies due to mineralization. The number of bands roughly divides the method into multispectral (typically 5–20 bands) or hyperspectral (from 20 to several hundred bands) remote sensing. The distance (D) between the sensor and the exploration target roughly divides the method into regional (satellite borne, D = hundreds of kilometers), local (airborne, D = some kms) or close-range (D = some dms) sensing. The ground resolution is typically from tens to hundreds of meters for regional data, from centimeters to meters for local data, and millimeters for close-range data.

In Finland, the following multispectral and hyperspectral remote/close-range sensing data have been used for mineral exploration, environmental research, or mineral species assessment:

- Landsat and Aster satellite regional multispectral data (VIS, NIR, SWIR, LWIR)
- EO-1 satellite regional hyperspectral Hyperion data (VIS, NIR, SWIR)
- HyMap and AISA airborne local hyperspectral data (VIS, NIR, SWIR)
- SisuROCK hyperspectral close-range imaging workstation data (VIS, NIR, SWIR, LWIR)
- Portable FieldSpecFR for close-range spectral single measurements (VIS, NIR, SWIR)

(Abbreviations: VIS = visual, NIR = near infrared, SWIR = short-wave infrared, LWIR = long-wave infrared)

Several published or archived spectral reflectance and emittance libraries are available for training the interpretation of these remote sensing data sets in mineral exploration and mining. LWIR close-range reflectance spectrometry, used in the characterization of selected mineral deposits, is reviewed in this volume by Kuosmanen et al. (p. 117).

Petrophysical database and detailed studies

Information on rock density and magnetic properties especially facilitates the interpretation of aeromagnetic and gravity surveys. Petrophysical sampling covers the whole of Finland and offers background information for the interpretation of the country-wide geophysical surveys. The petrophysical register currently includes measurement results of more than 130 000 bedrock samples: density, magnetic susceptibility and the intensity of remanent magnetization for different rock types, including information on the sampling site and rock type. Petrophysical properties of rocks mainly depend on the dominant rock-forming minerals and their relative concentrations, so that they can be used in characterizing different rock types in Finland (Airo & Säävuori 2013). The amount of petrophysical data at GTK is continually increasing as new measurements are conducted. The collection of data has also included some 200 samples from different ore deposit types. Although the number of different specific types is limited, their petrophysical properties nevertheless give background data for reference. The values of magnetic susceptibility for ore samples are an order of magnitude higher than those of common rock types, even that of ultramafic rocks. To complement the ore deposit data set, new measurements of ore samples were carried out for the current study and are also summarized here (see *Insert 6)*. In addition to surface petrophysics, GTK provides density and

Table 1. Applicability of different geophysical methods in the exploration of various mineral systems (modified from Ford et al. 2007).

🔴 Highly effective 🟡 Moderately effective 🔵 Generally ineffective

Geo-physical method	Air or ground	Appli-cation	Ni-Cu-PGE	Fe-Ti BIF	Gold	VMS	Olympic Dam-type	SEDEX	Por-phyry Cu	Pb-Zn	Dia-monds
Magnetic	Air	Geological framework	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴
		Direct targeting	🟡	🔴	🔵	🔴	🔴	🟡	🔴	🔵	🔴
	Ground	Geological framework	🟡	🔴	🔴	🔴	🔴	🔴	🔴	🟡	🔴
		Direct targeting	🟡	🔴	🟡	🔴	🔴	🟡	🔴	🔵	🔴
Electro-magnetic	Air	Geological framework	🔴	🔴	🟡	🟡	🔵	🟡	🔵	🔵	🟡
		Direct targeting	🔴	🔴	🟡	🔴	🟡	🟡	🔵	🔵	🔴
	Ground	Geological framework	🔴	🔴	🟡	🟡	🔵	🟡	🔵	🟡	🔴
		Direct targeting	🔴	🟡	🔵	🔴	🟡	🟡	🔵	🟡	🔴
Electric	Ground	Geological framework	🔴	🔵	🔵	🟡	🟡	🔵	🔵	🟡	🔵
		Direct targeting	🔴	🟡	🟡	🔴	🟡	🔵	🔴	🔴	🟡
Gravity	Air	Geological framework	🔴	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🟡
		Direct targeting	🔴	🔴	🔵	🔴	🟡	🟡	🔵	🟡	🔴
	Ground	Geological framework	🔴	🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴
		Direct targeting	🔴	🔴	🔵	🔴	🟡	🔴	🟡	🔴	🔴
Radio-metric	Air	Geological framework	🟡	🟡	🔴	🔴	🔴	🔴	🔴	🟡	🟡
		Direct targeting	🔵	🔵	🟡	🟡	🔴	🔵	🔴	🔵	🔵
	Ground	Geological framework	🟡	🔵	🔴	🟡	🔴	🟡	🔴	🔵	🔵
		Direct targeting	🔵	🟡	🟡	🟡	🔴	🔵	🔴	🔵	🔵
Seismic	Ground	Geological framework	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
		Direct targeting	🟡	🟡	🔵	🟡	🟡	🟡	🟡	🟡	🟡

magnetic property information on thousands of samples from exploration drill cores. One example of utilizing petrophysical data in characterizing propitious rock units for mineralization is the Lomalampi case by Salmirinne (2010) (Fig. 5).

Table 1 summarizes the application and suitability of different geophysical methods for the exploration of various mineral systems in Canada (based on Ford et al. 2007), and also gives an idea of their overall suitability in Finland. In general, the magnetic method is highly effective both for the impression of the geological framework and for direct targeting of most of the mineralization types. In general, electromagnetic, electric and gravity methods are effective for magmatic Ni-Cu-PGE and VMS deposits, and radiometrics and the magnetic method for porphyry Cu deposits.

Geophysical responses

Geophysical anomalies are primarily affected by the source mineralogy and secondly by source geometry and various factors determined by the geological conditions of the source body. The petrophysical properties of ore minerals and common associated host rocks provide information that makes it easier to understand the geophysical signatures of a certain deposit type (King 2007).

The likelihood of locating an ore deposit or its host rock by means of a geophysical anomaly depends on many factors, including the petrophysics of the ore minerals and their host rock, and the thickness and physical properties of the overburden cover. The size of the ore occurrence and its outcrop and the distance of its top from the ground surface are geometrical factors. The geology in the area and the anomalies caused by the country rocks, and the mode of occurrence of the ore deposit in relation to the anomalous rocks are geological factors (Ketola 1982).

Geophysical anomalies are described by their amplitude and form. The main factors influencing the amplitude and shape of geophysical anomalies include:

- *Source mineralogy and dimensions*: geophysically anomalous minerals contained in the source, their physical properties and texture (fabrics); size, geometry, depth of mineralization and its orientation relative to magnetic north, and the inclination of the Earth's magnetic field at its location.
- *Depth* of investigation of the method in question: depends on many factors, including system characteristics (*Table 2*).
- *Survey resolution*: the terrain clearance and flight line separation will affect the resolution of the detected geophysical anomalies.
- *Method footprint* – depends on the sampling density and the speed of aircraft.
- *Measurement techniques*: for example, the measurement frequency in frequency-domain electromagnetic measurements affects the response.
- *Wavelength* of the observed potential field. Geophysical responses for deeply buried sources decrease in amplitude and increase in spatial wavelength until they disappear into geological noise.
  - Effect of the observation level on the magnetic and gravity anomaly of a small and a large source body.
  - Short wavelength anomalies: shallow sources.

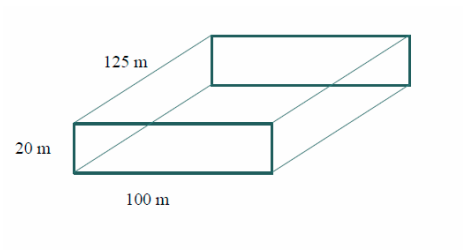
Modelling examples of gravity and magnetic anomalies at increasing depths for source bodies of different sizes and varying petrophysical parameters are collected in *Insert 1*. Magnetic or gravity methods are sensitive to completely different physical rock properties and they have very different roles in geological interpretation. The gravity method reveals information on the distribution of density and is routinely used for the identification of lithologies, structures and ore bodies themselves. The magnetic method is sensitive to the distribution of magnetic minerals and it is the main method for the interpretation of bedrock lithology and structure. Magnetic anomalies sometimes coincide with gravity anomalies, and rock alteration can cause a change in bulk density as well as magnetization. If the distributions of density or magnetization reflect geologically significant features, the interpretation of gravity and magnetic data can give 3D information on the distribution and structure of these features. The sources of gravity anomalies can be modelled from >1 km depth if the density difference between the source formation and the surroundings is great enough.

Table 2. Depth of investigation (general) for different geophysical methods.

Method	Typical source of anomaly	Depth of investigation
Magnetic	Magnetic susceptibility and/or remanent magnetization contrasts	From surface down to Curie isotherm
Gravity	Rock density contrasts	All below
Gamma-ray spectrometry	K, U and Th contrasts	Upper 50 cm
Electromagnetic (EM)	Lateral or vertical changes in Earth conductivity	GTK airborne EM system down to 70-100 m

Insert 1.
Modelling examples of gravity and magnetic anomalies for source bodies of different sizes and petrophysical parameters at increasing depths (in Kukkonen & Airo 2012, presentation at the GTK Academy, Espoo, Finland 12.12. 2011).

Case 1: 1Mton (small sized)



Modelling parameters:

Density of ore body 4000 kg/m^3 and country rock 2750 kg/m^3

susceptibility of ore body 30000 x 10^{-6} (Q=3), and of country rock 1000 x 10^{-6} (Q=0).

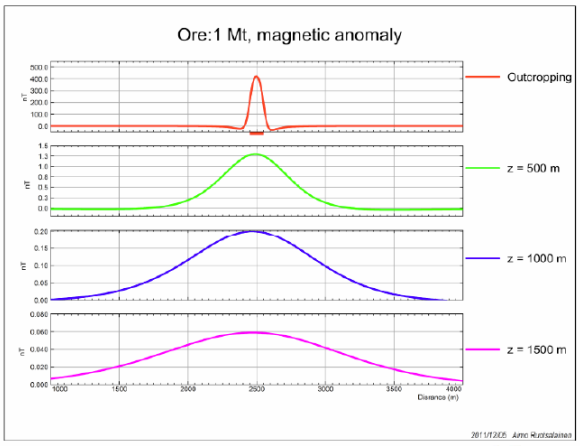
Outcropping source:

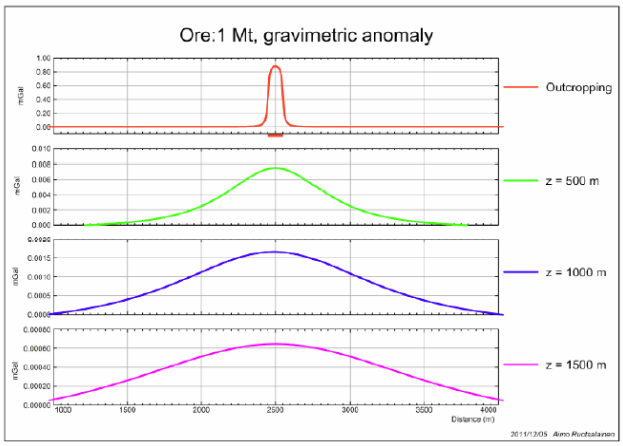
Magnetic anomaly 400 nT and 200 m wide, gravimetric anomaly 0.9 mGal.

At the depth of z = 500 m:

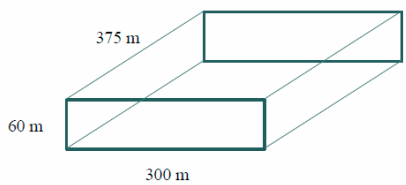
Magnetic anomaly 1.3 nT and 1 km wide, gravimetric anomaly 0.008 mGal.

Not detectable among other anomalies.





Case 2: 27Mton ("Outokumpu-size")



Modelling parameters:

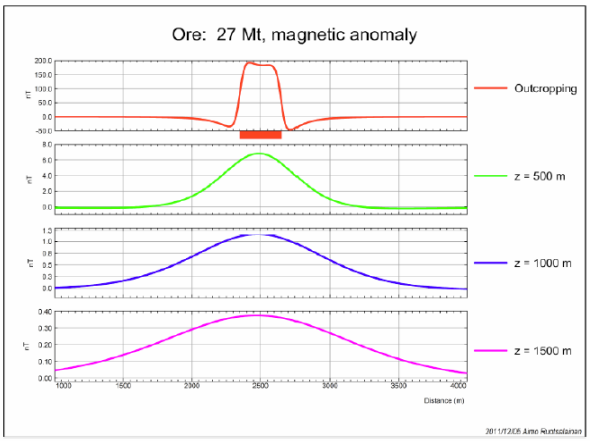
Density of ore body 4000 kg/m^3 and country rock 2750 kg/m^3

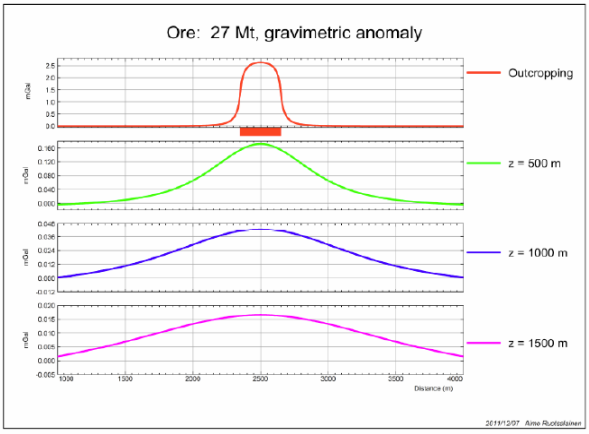
susceptibility of ore body 30000 x 10^{-6} (Q=3), and of country rock 1000 x 10^{-6} (Q=0).

Outcropping source:
Magnetic anomaly 200 nT and 500 m wide, gravimetric anomaly 2.5 mGal.

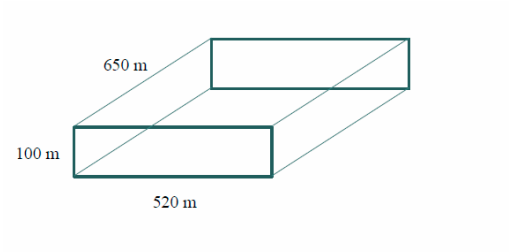
At the depth of z = 500 m:
Magnetic anomaly 7 nT and 1 km wide, gravimetric anomaly 0.16 mGal and 600 m wide.
Not easily detectable among other anomalies.

Insert 1. (cont)





Case 3: 135 Mton ("world class")



Modelling parameters:

Density of ore body 4000 kg/m^3 and country rock 2750 kg/m^3

susceptibility of ore body 30000 x 10^{-6} (Q=3), and of country rock 1000 x 10^{-6} (Q=0).

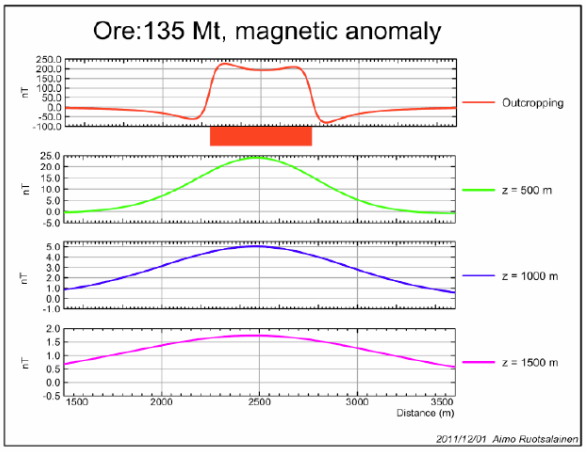
Outcropping source:

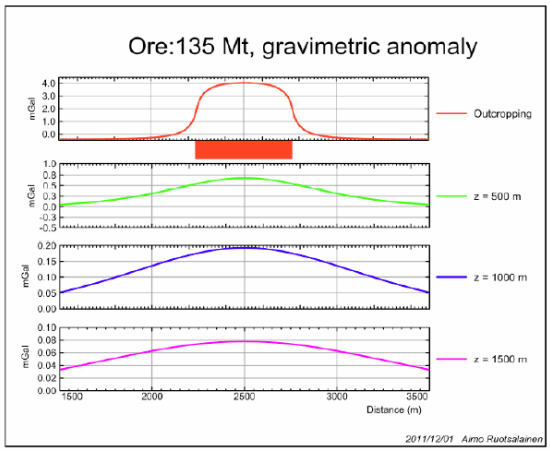
Magnetic anomaly 250 nT and 600 m wide, gravimetric anomaly 4 mGal, 600 m wide.

At the depth of z = 500 m:

Magnetic anomaly 25 nT and 1.5 km wide, gravimetric anomaly 0.8 mGal.

Not detectable among other anomalies.





Geophysically relevant minerals

The physical properties of minerals that are relevant for the physical properties of rocks and ores are reviewed in the following. These properties include density, magnetic properties, electrical properties, radioactivity and seismic velocity.

Different rock types often have distinctive and characteristic physical properties, as illustrated for density and magnetic susceptibility in Figure 1 (from Airo & Säävuori 2013). This reflects the iron content, bound either in rock-forming minerals or in ore minerals. Density depends on the proportional content of Fe and Mg-bearing minerals in the rock's main mineral composition, so that in each rock class the mean densities increase due

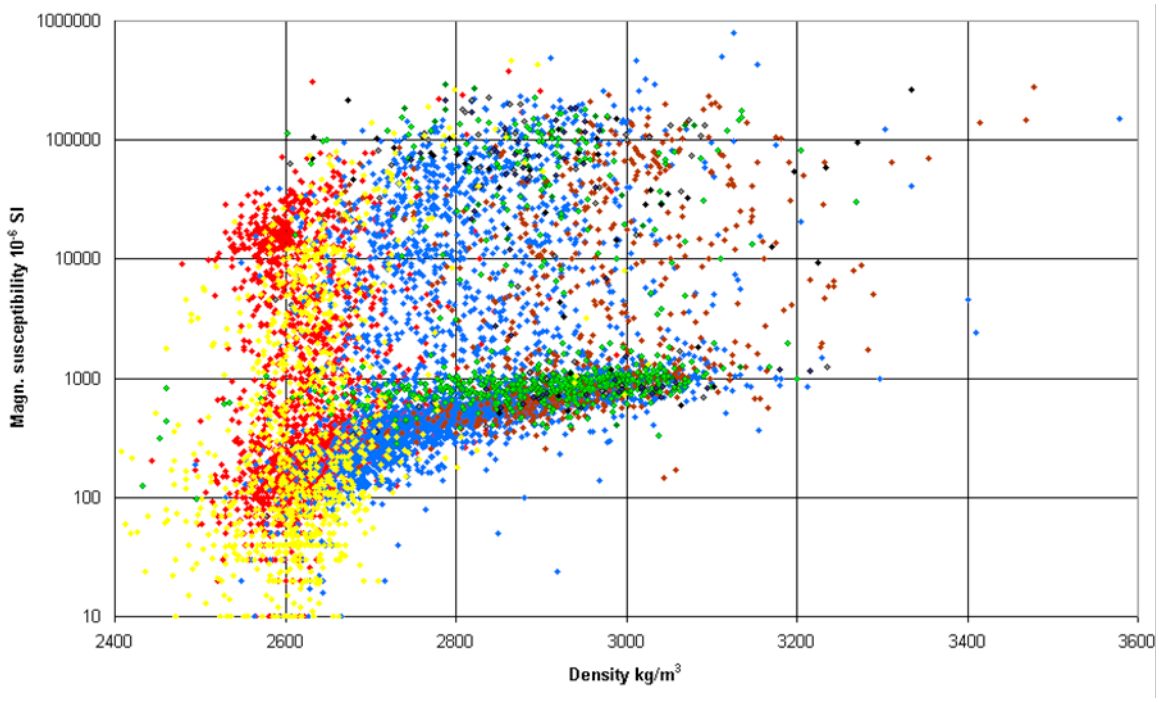


Fig. 1. Ranges of density and magnetic susceptibility of rock classes from GTK's petrophysical database. The densities of quartzites (yellow) and granites (red) are mainly below 2700 kg/m^3 and the densities above 2800 kg/m^3 characterize mica schists (blue), metavolcanic rocks (green), gabbros (brown) and ultramafic rocks (black). The susceptibility distribution is bimodal, with a lower susceptibility mode caused by the paramagnetism of rock-forming silicates, and a higher mode that is due to ferrimagnetic minerals.

Table 3. Ore mineral and host rock densities (g/cm^3) and magnetic susceptibilities (10^{-6} SI) (after King 2007 and Morgan 2012). Typical susceptibility and density values for country rocks in Finland from Airo & Säävuori 2013.

Mineral	**Density g/cm^3**		**Susceptibility 10^{-6}**	
Sulfides / Oxides	Range	Average	Range	Average
Chalcopyrite	4.1-4.3	4.2	300 - 400	
Pentlandite		4.8		< 1000
Pyrite	5.02		-6 - 100	
Pyrrhotite	4.5-4.8	4.65	up to 6 000 000	
Pyrrhotite (mono)				700 000
Pyrrhotite (hex)				2000
Sphalerite		4	-15 - 2000	
Magnetite		5.18	1 000 000 - 15 000 000	3 000 000
Hematite		5.26	1300 - 7000	
Maghemite				up to 3 000 000
Ilmenite			1000 - 8000	
Host rocks				
Felsic igneous	2.3-3.11	2.61	500 - 80 000	
Mafic igneous	2.09-3.17	2.79	1000 - 100 000	
Ultramafic rocks(peridotite)	2.78-3.37	3.15	10 000 - 100 000	

to an increase in the proportion of mafic minerals. Similarly, magnetic susceptibility depends on the proportional content of mafic / felsic rock-forming minerals, but in addition on the iron bound in magnetic minerals. Iron sulphides and iron oxides (mainly magnetite) are the principal ore minerals, and have distinctive physical properties. Of the other geophysically distinctive minerals that may be related to ore mineralization, graphite in metamorphosed graphitic shales (black schists) might, for example, also have a strong impression for geophysics. The clustering of rocks into specific ranges of density and magnetic susceptibility is typical for Precambrian, metamorphic and highly deformed terrains (also Reeves 2005).

Density of ore minerals

The densities of common ore minerals are all above 4.0 g/cm^3, so that their presence increases the bulk density of rock. Of the common ore minerals, magnetite, pyrrhotite and pyrite all have densities ~5 g/cm^3, and cannot be separated by the gravimetric method, but their magnetic properties deviate characteristically. The density and susceptibility ranges for common ore minerals and some typical host rocks are shown in *Table 3*.

Magnetic minerals

Minerals that can cause a significant magnetic response are magnetite, pyrrhotite, hematite, ilmenite/titanohematite and maghemite. Pyrite is non-magnetic, but can be metamorphosed to pyrrhotite at upper greenschist-lower amphibolites grades. Pyrrhotite can be metamorphosed to magnetite (Clark 1997, Gunn & Dentith 1997). Table 4 compares the magnetization type and susceptibility of various magnetic or rock-forming minerals. Fe,Mg-bearing silicates are generally paramagnetic and only reach a maximum susceptibility level of 0.001–0.002 x 10^{-6}. The same level is, however, reached by a magnetite concentration as low as 0.01% (Hrouda et al. 2009). Thus, even a minor concentration of ferrimagnetic minerals has a dominant effect on the magnetic susceptibility of rock.

Of the two types of magnetization that exist, induced magnetization is proportional to the susceptibility of the material being magnetized and can be in the same direction as the Earth's field. Remanent (permanent) magnetization can have any direction and it is carried by ferrimagnetic minerals. In certain cases, remanent magnetization can be orders of magnitude greater that the induced.

The ferrimagnetic susceptibility of rocks depends on:

- the magnetic mineral type and content (seldom >10%)
- the measuring field and temperature
- the grain size of ferrimagnetic minerals
- the content of iron in rock (principally, but in a complex way).

The amplitude and shape of a magnetic anomaly can be strongly affected by remanent magnetization, which may be useful to take into account in magnetic modelling. The ratio of remanent to induced magnetization (Königsberger ratio, Q-value) can be used to predict the magnetic mineralogy in the anomaly source simply by using the information based on petrophysical laboratory

Table 4. Magnetization type and susceptibility (from Reeves 2005, Clark 1997 and Schön 2004).

Minerals	Magnetic susceptibility (SI)		Magnetization type
Magnetite Magnetite ore	15 (pure) 0.07-14	Positive, very high, complex function of the magnetizing field	Ferrimagnetic
Pyrrhotite (monoclinic)	0.001- 1	Positive, may be high	Ferrimagnetic
Hematite Hematite ore	0.013-0.07 0.0004 - 0.01	Positive relatively low	Antiferromagnetic
Ilmenite Ilmenite ore	0.01- 0.08 0.3 - 4	Positive relatively low	Antiferromagnetic
Rock-forming Fe,Mg-silicates	< 0.001	Positive, relatively low, independent of the magnetizing field	Paramagnetic
Quartz, calcite, graphite, tremolite		Negative and independent of the magnetizing field	Diamagnetic

Table 5. Magnetic susceptibilities for selected diamagnetic and paramagnetic minerals (modified from Clark 1997 and Schön 2004). The susceptibilities are in 10^{-6} SI-units.

Diamagnetic	Susceptibility average	Paramagnetic	Susceptibility range
Quartz	-15	Garnet	500-6000
Orthoclase	-10	Muscovite	30-700
Calcite	-13	Biotite	800-3000
Forsterite	-13	Pyroxenes	500-5000
Galena	-33 (to 9)	Olivine	100-4000
Sphalerite	-13	Amfiboles	600-5000
Graphite	-70 (to -180)	Pyrite	-10-60
		Chalcopyrite	300-400

measurements. Ferrimagnetic minerals (magnetite, monoclinic form of pyrrhotite) are typically associated with significant remanence, and metamorphic and alteration processes often affect the remanent magnetization by modifying the concentration of grain sizes of these minerals. A high metamorphic grade produces fine-grained magnetite (magnetite content grows + the amount of fine-grained magnetite increases). Ferrimagnetic minerals also are a typical constituent in common rock types. For example, Q-ratios are between 1 and 10 for plutonic and dyke rocks, and for volcanic and metasedimentary rocks (Airo & Sääsvuori 2013). For metamorphic and altered rocks (schists with monoclinic pyrrhotite and skarns), as well as rocks bearing ore minerals, Q-values sometimes reach into the hundreds. In a broad sense, particularly strong remanence in rocks is either due to monoclinic pyrrhotite or fine-grained magnetite. A decreased remanence is typical for shear zones or any zones of hydrothermal alteration. As deformation may have an influence on the magnetic mineralogy of rocks, knowledge of rock properties and their variation helps to focus more detailed investigations.

Very weak rock susceptibilities most probably contain a component due to the diamagnetic behaviour of some minerals. In diamagnetism, the magnetic moment vector tends to be in the opposite direction to the magnetizing field (*Table 5*). Quartz, which is present in many rocks, is a typical diamagnetic mineral, and graphite is a common diamagnetic mineral in metamorphosed shales. Of the ore minerals, galena and sphalerite are diamagnetic. Pyrite has a very low susceptibility and tends to lower the rock susceptibility.

Electrical conductivity of metallic minerals

Electrical and electromagnetic methods observe the distribution of the electrical conductivity in the ground. In normal rocks, the electric current flows by ionic conduction in the electrolyte in the pores of the rock. However, certain minerals have a measure of electronic conduction (almost all the metallic sulphides (except sphalerite) such as pyrite, graphite, some coals, magnetite, pyrolusite, native metals, some arsenides, and other minerals with a metallic lustre). Even small quantities of metallic ore minerals can significantly affect the bulk resistivity of geological materials. Of all the geophysical properties of rocks, electrical resistivity is by far the most variable and it depends on many factors, including the rock type, porosity, the connectivity of pores, the nature of the fluid, and the metallic content of the solid matrix. Values ranging by as much as 10 orders of magnitude may be encountered, and even individual rock types can vary by several orders of magnitude (Fig. 2). The measurement procedure also affects these parameters, so that the reported values of these parameters may show some variation in different studies.

Most metallic ore minerals are electronic semiconductors. Their resistivities are lower than those of metals and highly variable, because the inclusion of impurity ions into a particular metallic mineral has a significant effect on the resistivity (Palacky 1987). Information on the conductivity properties of important ore minerals is summarized in the following fact sheet (based on Oldenburg & Jones 2007 and Palacky 1987). The range of resistivity and conductivity of typical ore minerals is shown in Table 6 and the range of IP chargeability in Table 7. IP measures the chargeability of the ground, i.e. how well materials tend to retain electrical charges. Measurements are made either

in the time domain or the frequency domain; their units are respectively milliseconds (msec) and the percentage frequency effect. In general, disseminated sulphides have very good induced polarization responses.

Although metallic minerals (particularly sulphides) may be conductive, there are at least two reasons why ore-grade deposits of these minerals may not be as conductive as expected (Palacky 1987). In theory, massive sulphides should have lower responses, but in practice they may have very good responses. This is due to the mineralization halo generally surrounding massive sulphides (Ford et al. 2007). Sulphide deposits can be either disseminated or massive. In disseminated sulphides, the mineral occurs as fine particles dispersed throughout the matrix, and they may be resistive or conductive. In massive sulphides, the mineral occurs in a more homogeneous form, and they are likely to be conductive. Chemical and/or thermal alteration can convert metallic minerals into oxides or other forms that are not as conductive as the original minerals. The selection of the electromagnetic method may have a crucial effect on the success of the operation, depending on the target.

Electrical properties of important ore minerals

- Pyrrhotite (FeS) is a consistently highly conductive mineral.
- Graphite (C) is a true conductor, like a metal (i.e. not a semiconductor like ore minerals), and it is very conductive, even at very low concentrations. It is also chargeable, and it is notoriously difficult to distinguish from metallic ore minerals. Graphite is a metallic conductor with a resistivity of 10^{-4} to 5×10^{-3} Ωm and is found in many crustal rocks. Graphite occurs in metamorphic rocks and is difficult to distinguish from metallic ore minerals. The substitution of impurity ions into the lattice of a particular metallic mineral may have a significant effect on the resistivity.
- Pyrite (FeS_2) is the most common metallic sulphide and has the most variable conductivity. Its conductivity is generally higher than that of porous rocks. Pure pyrite has a resistivity of about 3×10^{-5} Ωm, but mixing in minor amounts of copper can increase the resistivity by six orders of magnitude to 10 Ωm.
- Galena (PbS) and magnetite (Fe_3O_4) are conductive as minerals, but much less conductive as ore because of their loose crystal structures.
- Other conductive minerals include bornite ($CuFeS_4$), chalcocite (Cu_2S), covellite (CuS), ilmenite ($FeTiO_3$), molybdenite (MoS_2), and the manganese minerals holandite and pyrolusite.
- Hematite and zincblende (sphalerite) are usually nearly insulators.
- Gold (Au) has among the most anomalous physical properties: its density is 19 300 kg/m^3 and electrical conductivity 5×10^7 S/m. The conductivity of an iron formation may reach very high values: min 0.05 to max 3300 mS/m.

(based on Oldenburg & Jones 2007 and Palacky 1987)

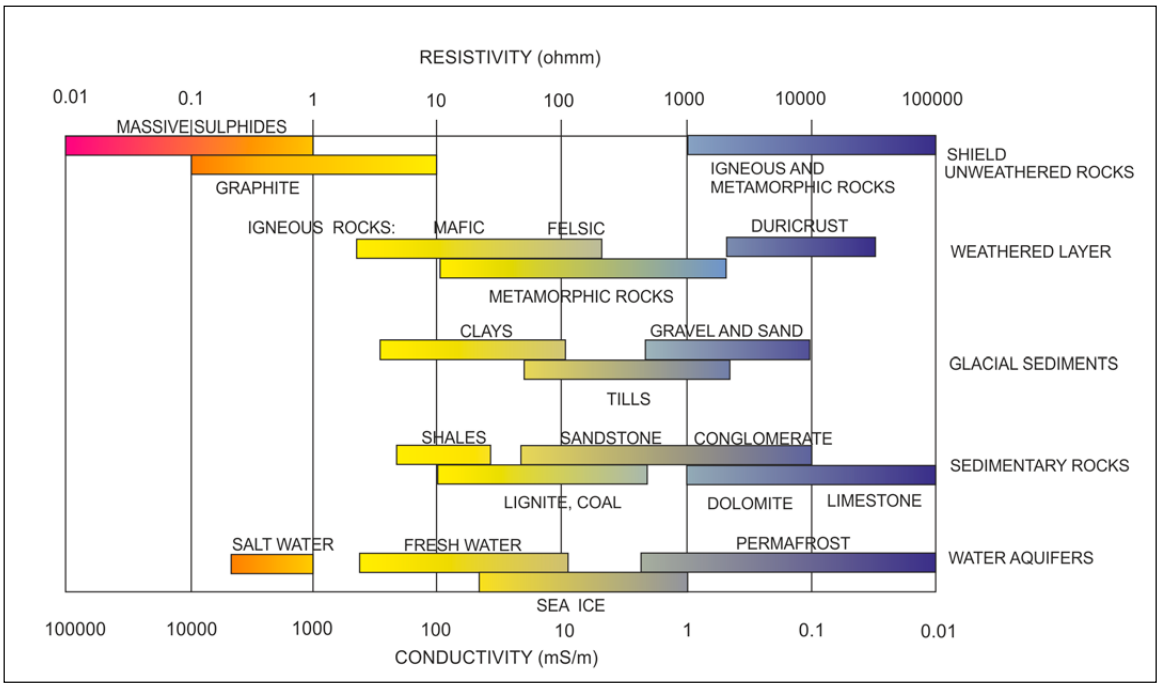


Fig. 2. Resistivities (conductivities) of rocks and earth materials (after Oldenburg & Jones 2007).

Table 6. Resistivities and conductivities of selected metals and minerals (modified from King 2007 and Peltoniemi 1988).

Resistivity of selected ore minerals (King 2007)		**Electrical conductivity of selected metals and minerals (Peltoniemi 1988)**	
Minerals	**Resistivity (Ohm-m)**	**Material**	**Typical conductivity, S/m**
		Gold	$50 \cdot 10^{6}$
		Copper	$3 – 80 \cdot 10^{6}$
		Graphite	10^{2} - 10^{6}
Chalcopyrite, CuFeS2	$1.2 \times 10^{-5} – 0.3$	Chalcopyrite	10 - 10^{4}
Pyrite, FeS2	$3.0 \times 10^{-5} – 1.5$	Pyrite	1 - 10^{5}
Magnetite, Fe3O4	$5.0 \times 10^{-4} – 5.0 \times 10^{4}$	Magnetite	10^{-4} - 10^{5}
		Mica	$10^{-3} – 10^{-14}$
		Quartz	$10^{-10} – 10^{-14}$
Hematite, Fe2O3	3.5×10^{-3} - 10^{7}		
Galena, PbS	$3.0 \times 10^{-5} – 3.0 \times 10^{2}$		

Table 7. Relative IP chargeability for common ore minerals and rocks (after King 2007 and Oldenburg & Jones 2007).

Material type	**Chargeability (msec)**	**Material type**	**Chargeability (msec)**
Chargeability of minerals at 1% concentration in the samples		*Charging and discharging times about one minute each (much longer than field survey systems), therefore values are larger than field measurements*	
Pyrrhotite	~10	20% Sulphides	2000 - 3000
Pentlandite	~10	8-20% Sulphides	1000 - 2000
Pyrite	13.4	2-8% Sulphides	500 - 1000
Copper	12.3	Volcanic tuffs	300 - 800
Graphite	11.2	Sandstone, Siltstone	100 - 500
Chalcopyrite	9.4	Dense volcanic rocks	100 - 500
Magnetite	2.2	Shale	50 - 100
Galena	3.7	Granite, Granodiorite	10 - 50
Hematite	0.0	Limestone, Dolomite	10 - 20

Radioactive minerals

Gamma-ray spectrometry can provide direct quantitative measures of the natural radioelements potassium (K), thorium (Th) and uranium (U). In general, felsic (acid) and intermediate rocks commonly show higher mean radioelement concentrations than mafic (basic) or ultramafic rocks and can be outlined on the basis of their radiometric patterns (Dickson & Scott 1997). Examples of both depletion and enrichment of the three radioelements have been reported. Hydrothermal alteration and mineralizing processes can affect the radioelement content, with K being the most easily affected. For instance, the potassium content increases in altered rocks surrounding both base metal and Au deposits. Thorium may be mobilized during mineralization processes, being partly depleted in areas of K-alteration or intense silicification, but concentrated in Th-rich materials such as laterite (Gunn & Dentith 1997). Where sulphide minerals are present, their oxidation accelerates uranium mobilization (Killeen 1979). Uranium and (or) potassium are commonly enriched in or adjacent to some ore deposits, and their presence may often be used in indirect targeting. Geological processes leading to various styles of mineral deposits may result in variations in radioelement contents. In particular, radioelement signatures are modified by weathering processes. The search for U and Th deposits involves the direct use of airborne gamma-ray surveys in mineral exploration, where elevated concentrations of these elements or element ratios (e.g. Th/U or K/U) are searched for. The radioactivity of minerals is further reviewed in Lauri & Turunen in this volume (*p. 107*).

Seismic velocity of rocks and ore minerals

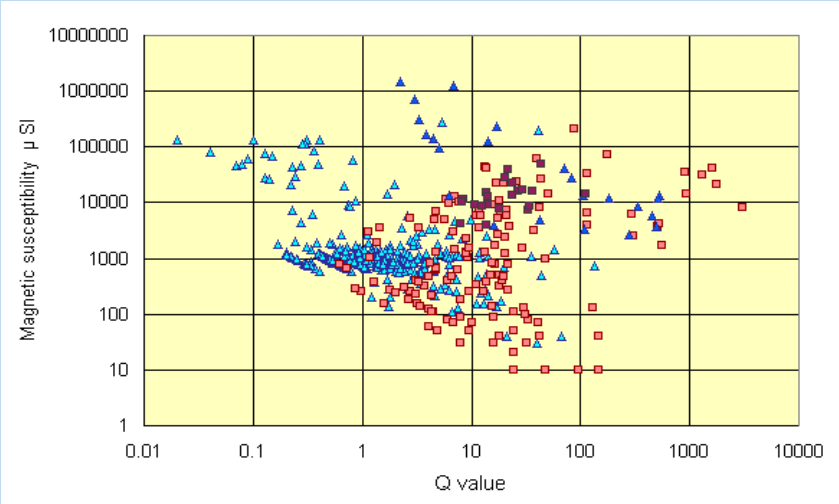
The application of seismic methods for mineral exploration has good potential, as these methods are capable of imaging mineral deposits at various depths. The average velocities of acoustic waves in igneous and metamorphic rocks typically increase with density. For example, velocities for ultramafic rocks, with densities ranging from 3.0 to 3.5 kg/m^3, are in the category of 8 km/s, and for serpentinites (with densities below 3 kg/m^3), the velocities are in the range of 5–6 km/s (Milkereit et al. 2000). Most economically significant sulphides and pyrrhotite are all uniformly of very low velocity. This makes them ideal targets for crosshole transmission seismic tomography, which measures only velocity. Because they are also anomalous in density, they produce acoustic reflectivity anomalies. However, as stated by King (2007), since acoustic reflectivity is proportional to the acoustic impedance (product of velocity x density), their high densities and lower velocities can result in reduced reflectivity. Sulphide ores and the concentration of certain Fe oxides, because of their high density, have higher acoustic impedance with respect to surrounding rocks. Massive ore mineralization with a relevant size and geometry should produce a strong seismic response in many geological situations (Milkereit et al. 2000, Salisbury et al. 2000). The contrast of acoustic impedance between felsic and mafic rocks is also significant; this allows an opportunity to detect mafic intrusions: dykes or sills. The high acoustic impedance of massive mineral deposits, which has been disclosed by laboratory measurements, should also be confirmed by *in situ* measurements from borehole logging.

Magnetite or pyrrhotite as anomaly sources

The magnetic properties of rocks yield abundant information on the source minerals, their grain size and texture, and the age of magnetization. When the petrophysical properties of rocks bearing magnetite or pyrrhotite as their main magnetic minerals are compared, a general clustering of pyrrhotite- or magnetite-bearing rocks can be observed. Their remanent magnetization is an effective discriminator. The ferrimagnetic type of pyrrhotite may be associated with intensive remanence, and hence with extremely high Königsberger ratios, even up to thousands. In contrast, the intensity of remanent magnetization of magnetite, particularly if coarse grained, may be much lower. This fact can be used in predicting magnetic mineralogy from petrophysical plots. In Figure 3, Q-ratios of 1 to 2 denote an equal contribution of remanent and induced magnetization to the intensity of the magnetic anomaly. Samples with coarse-grained magnetite typically have Q-ratios below 1, but the Q-ratios increase as a function of decreasing magnetite grain size. Samples that contain monoclinic pyrrhotite typically have Q-ratios close to ten or above. Fine-grained magnetite may also be associated with a strong remanent component. This means that if magnetite and monoclinic pyrrhotite are present together in the same anomaly source body, it may be difficult to sepa-

rate them only on the basis of magnetic properties. Thermomagnetic tests to identify the monoclinic /hexagonal type of pyrrhotite have been carried out for mineralized black schists from several locations in eastern Finland, and the monoclinic type of pyrrhotite appears to be more prevalent (Airo & Loukola-Ruskeeniemi 2004).

Säävuori et al. (1991) correlated magnetic and electrical conductivity anomalies and petrophysical properties of sulphide-bearing rocks from 7 targets in Finland. The samples could be divided into two main categories on the basis of their susceptibilities and Q-ratios: 1) a magnetite population and 2) a pyrrhotite population (with pyrrhotite-dominant and pyrite-dominant subcategories). The anomalies selected for sampling and analysis consisted of plutonic, metasedimentary and metavolcanic rocks, of which about one-third comprised mica gneisses and one sample was composed of graphitic black schist. In almost 100 sulphide-bearing samples, the relative proportions of different iron-bearing sulphides and magnetite were distinguished. The results demonstrate that sulphides may be a considerable source of conductivity anomalies, and that magnetite, when present with pyrite, may also be related to conductivity anomalies.



Blue samples:
Magnetite-bearing dolerites and iron ore samples

Red samples:
Pyrrhotite-bearing black schists and VMS samples

Q = Jr/Ji
Ji = Induced magnetization
Jr = Remanent magnetization

Q ~1-2	Equal contribution of remanent and induced magnetization on magnetic anomaly intensity
Q <1	Coarse-grained magnetite, remanence has irrelevant effect on magnetic anomaly
Q >>1	Fine-grained magnetite or monoclinic pyrrhotite (Q ~10 and susc. > 10 000 µSI); remanence has strong effect on magnetic anomaly intensity and shape

Fig. 3. Comparison of susceptibilities and Königsberger ratios of typical magnetite- or pyrrhotite-bearing rocks and their importance to the magnetic anomaly intensity and shape. Sampled from the Finnish National Petrophysical Database.

Tools for visualization and anomaly enhancing

For the purpose of introducing geophysical signatures related to different mineral systems, the magnetic total intensity image may in itself be very expressive, particularly so as a grey-scale presentation. These images are sensitive to delicate magnetic patterns and signatures that may be related to mineralization. However, additional information may be obtained by using some mathematical tools to enhance certain geophysical signatures or suppressed geological features. These common tools include potential field derivatives, frequency filters, upward continuation or spatial derivatives. To analyse shallow geological structures, short frequencies are enhanced, and to extract deep features, the regional, long-wavelength structures are enhanced. The following inserts illustrate ways of processing data sets and their combinations, and these are applied throughout this report in outlining the geophysical footprints of mineralization styles.

Insert 2 is an example of the integrated use of airborne magnetic and electromagnetic data sets in the visualization of an ultramafic intrusion in northern Finland (Airo & Kurimo 1999). The ability of GTK's electromagnetic data to be used in calculating the apparent susceptibility is useful when *in situ* petrophysical measurements are lacking. The remanent magnetization was suspected to affect the magnetic anomaly related to the intrusion. Field checking verified that the magnetite-bearing part of the anomaly could be outlined by using the magnetite effect. The effect of remanence was excluded by calculation of the apparent susceptibility on the basis of the electromagnetic data.

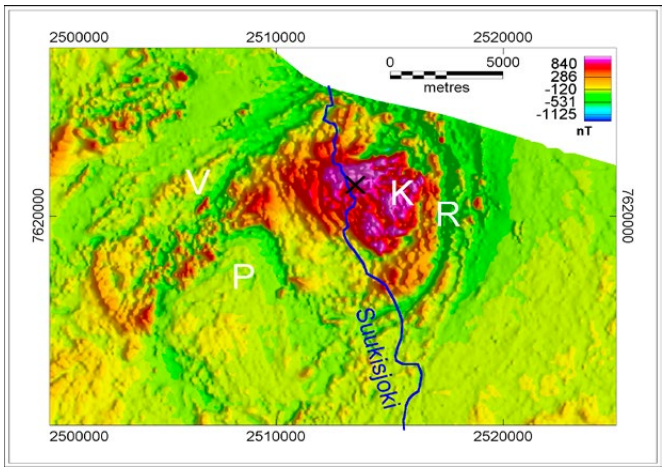
Insert 3 shows a collection of composite maps with mineral deposits, in which techniques for enhancing surface features in airborne geophysical data have been applied. This collection displays various thematic and integrated maps produced from GTK's airborne magnetic, electromagnetic and radiometric datasets. These may be useful in analysing geophysical surface anomalies and comparing geophysical information with observed geology. Classified electrical conductivity anomalies are also widely used in this report (e.g., Fig. 4b).

Insert 4 describes how the electromagnetic response can be used in distinguishing rocks with magnetite or pyrrhotite as their main magnetic mineral. Remanence affects the style of magnetic anomalies (magnetic anomaly intensity and shape). In the lower part of the aeromagnetic map "A", magnetic anomalies are due to magnetite, whereas in the upper part they are due to monoclinic pyrrhotite. This is verified by conductivity categories in map "B", in which pyrrhotite-caused anomalies are associated with electromagnetic anomalies indicating conductivity. In the case of coarse-grained magnetite, with Q-values below unity, the magnetic anomaly depends almost entirely on the induced magnetization, and in this case the anomaly signatures are smooth. Along with decreasing magnetic grain sizes, the remanent magnetization becomes more dominant. This brings sharp gradients and variation in anomaly intensities due to alternating directions of remanence. This is why the magnetic anomalies due to pyrrhotite or due to fine-grained magnetite are very similar.

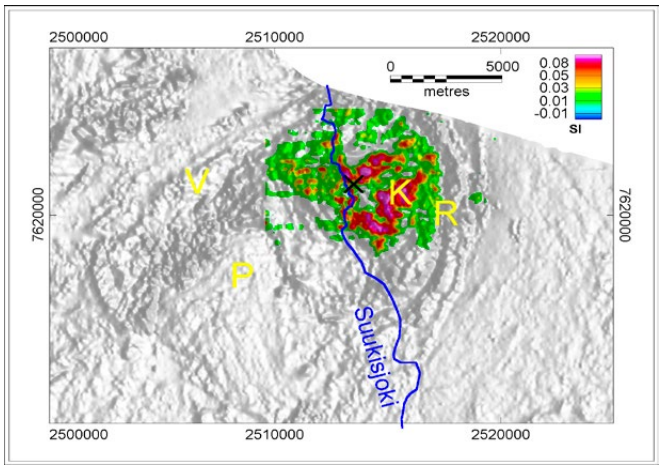
The GTK frequency-domain airborne electromagnetic system provides a possibility for classifying electromagnetic anomalies as conductive or non-conductive. Map "C" shows the classification of anomalies on the basis of the ratio of the real (Re) to the imaginary (Im) component of electromagnetic data (Re/Im). The phenomenon is based on the negative response in the real component at low conductivity and with high magnetic permeability (the so-called magnetite effect, diagram "D") (Suppala et al. 2005, Leväniemi et al. 2009). Although magnetite has intrinsically high conductivity, magnetite grains are rarely well electrically connected in unaltered intrusive rock. Even nearly massive magnetite can be relatively resistive, despite its high intrinsic conductivity.

Insert 5 displays techniques for the detection of magnetic anomalies of a certain type: extremely high amplitudes + expected remanent magnetization (Airo et al. 2014). This type of classification is constantly used in this report (*Insert 9* for the whole of Finland and, for example, Fig. 4a). The highly magnetic anomaly source rocks may be, for instance, serpentinite bodies, ultramafic intrusions with abundant magnetite, or iron-bearing formations (iron ore, BIF, magnetite type IOCG).

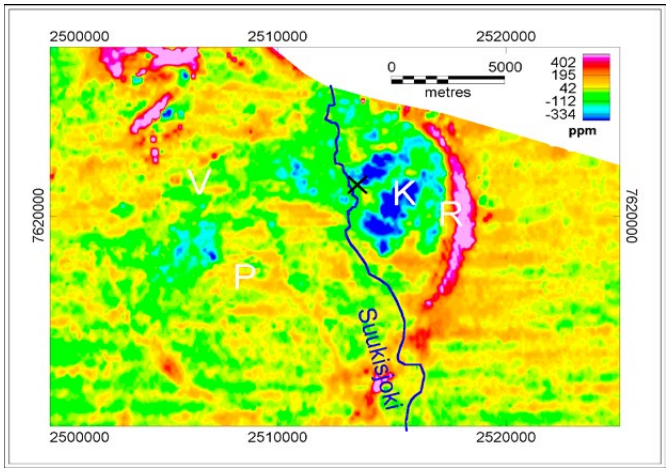
Insert 2.
Palaeoproterozoic mafic-ultramafic intrusion Suukisjoki, Finnish Lapland (from Airo & Kurimo 1999).



Aeromagnetic anomaly map showing the mafic-ultramafic intrusion.
K: magnetic anomaly influenced by both induced and remanent magnetizations
R: electrical conductivity + weak magnetization
V: weak magnetization
P: weakly magnetic country rocks



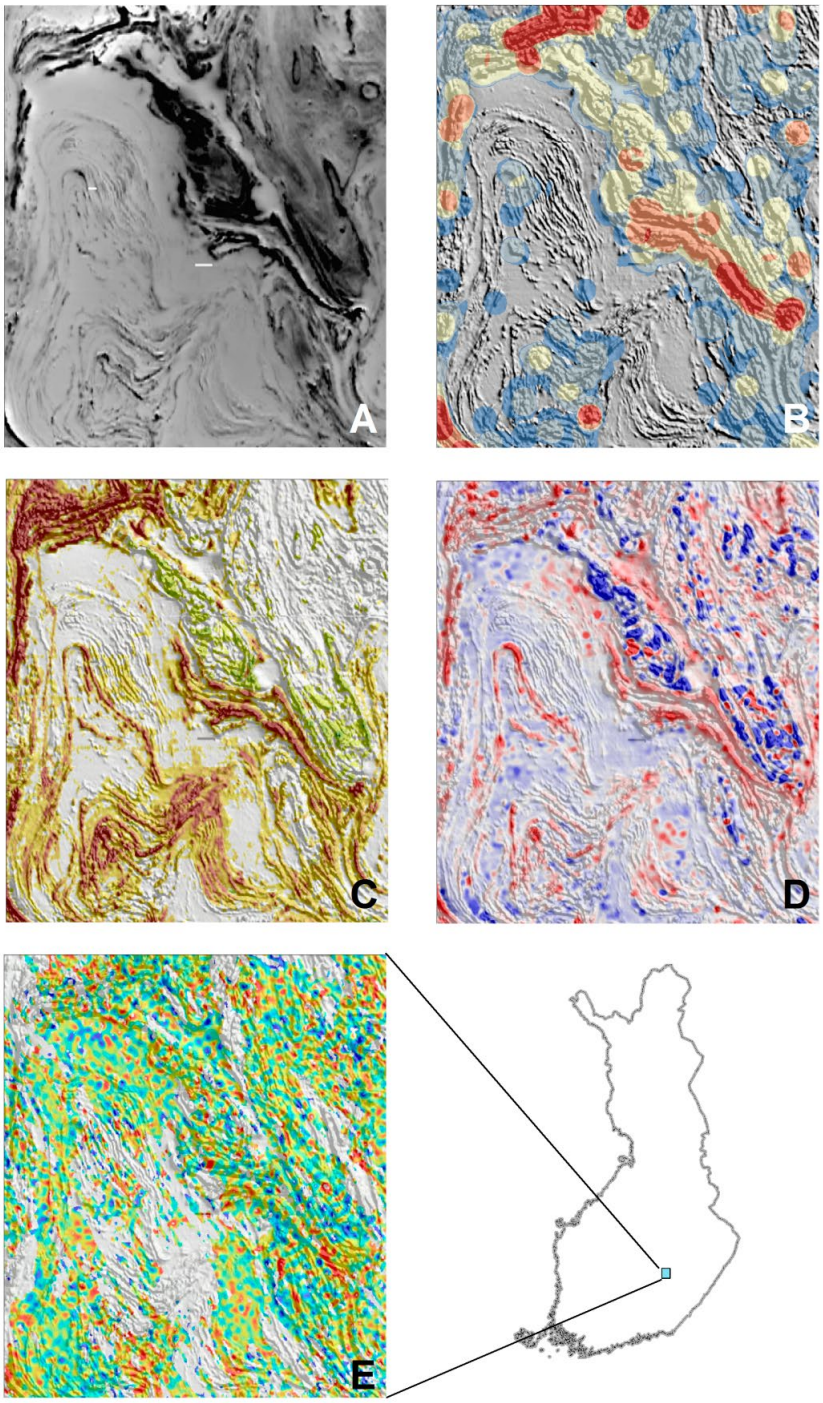
EFFECT OF REMANENCE EXCLUDED:
Apparent susceptibility was calculated from negative airborne electromagnetic in-phase component. The highest susceptibility (K) is shown in the colour overlay on the magnetic derivative map. Overall susceptibility was calculated from the negative AEM in-phase data as 0.05 SI (formulas by Keller & Frischknecht 1966)



Airborne electromagnetic in-phase (real) component shows negative response over the magnetite-bearing ultramafic intrusion (K). It corresponds to the high susceptibility parts of the intrusion. The conductivity anomaly (R) is based on pyrrhotite in country rocks.

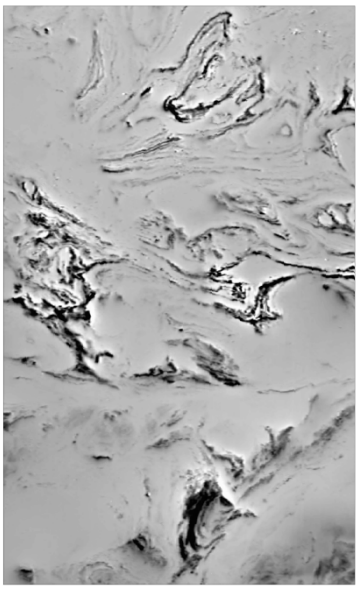
Location of the example anomaly in northern Finland.

Insert 3.
Detailed airborne geophysical signatures denote close-to-surface features of ground. Special techniques may be used for enhancing subtle signatures. The map layers for whole of Finland have been prepared by E. Hyvönen, GTK. Map area is 25 km x 30 km.

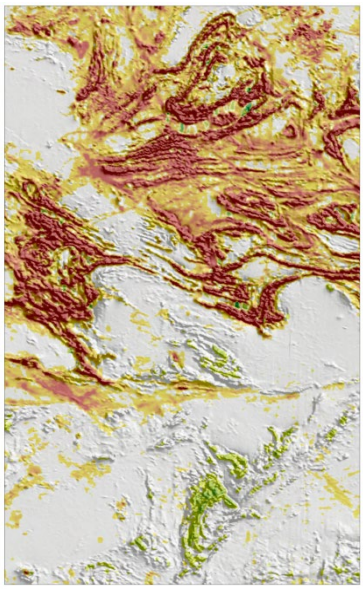


A. Aeromagnetic grey-scale image (dark = high intensity anomaly). Notice the ring-like magnetic anomaly in the right upper corner; it will be discussed in more detail in Insert 13.
B. Classification of magnetic anomalies. Red = high amplitude (techniques and colour categories are explained in Insert 5).
C. Electromagnetic classified real component (red/brown = good conductivity: green = low conductivity). Low-amplitude noise has been removed.
D. Electromagnetic ratio map (Real/Imaginary components). Red = good conductivity; blue = low (no) conductivity.
E. Aeroradiometric image: uranium (cut-off).

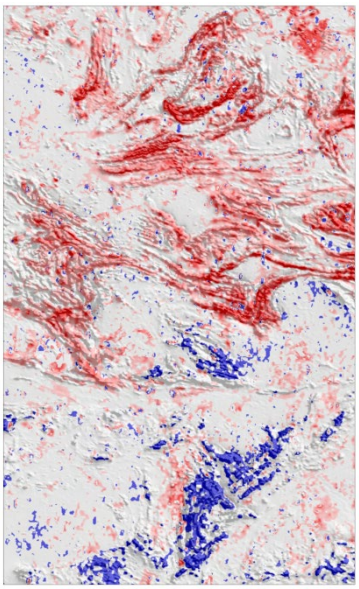
Insert 4.
Magnetite or pyrrhotite? How to use the electromagnetic response to distinguish rocks with magnetite or pyrrhotite content.



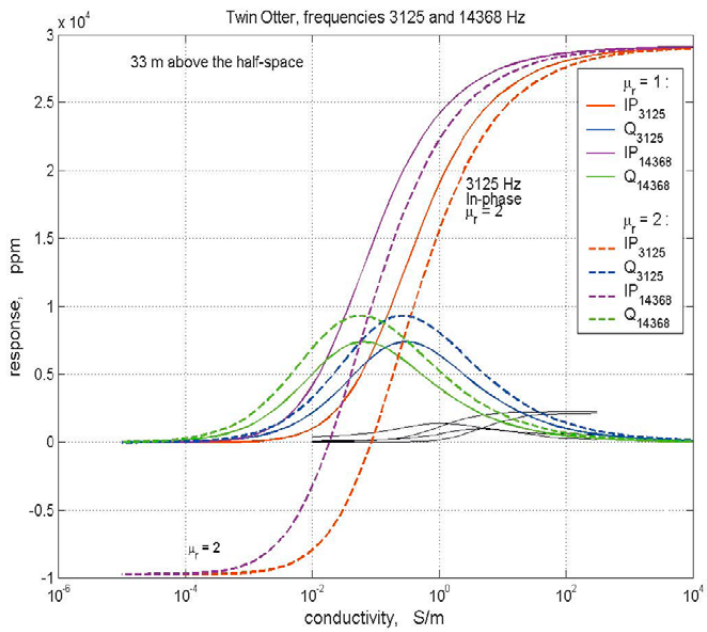
A. Aeromagnetic grey-shaded image. Dark shades denote high anomaly intensity.



B. Electromagnetic classification image (real component).
Electrically conductive zones (pyrrhotite and graphite bearing rocks) in red/brown; low conductivity (magnetite bearing rocks) in green.



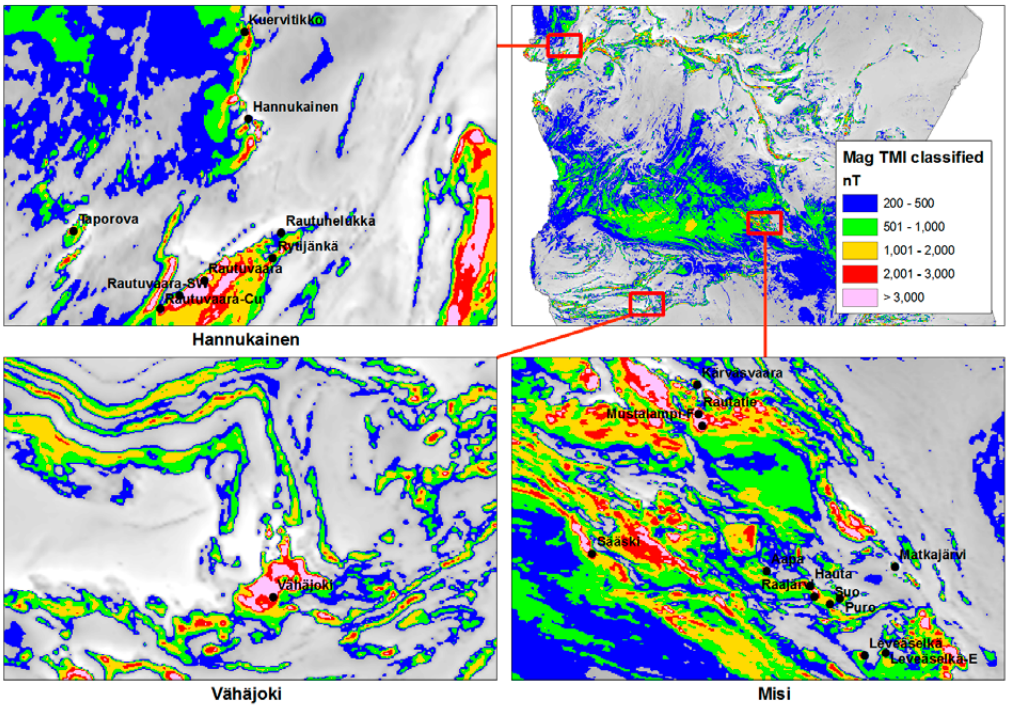
C. Electromagnetic Re/Im ratio (ratio of the Real to the Imaginary component). Red = good conductivity; blue = no conductivity.



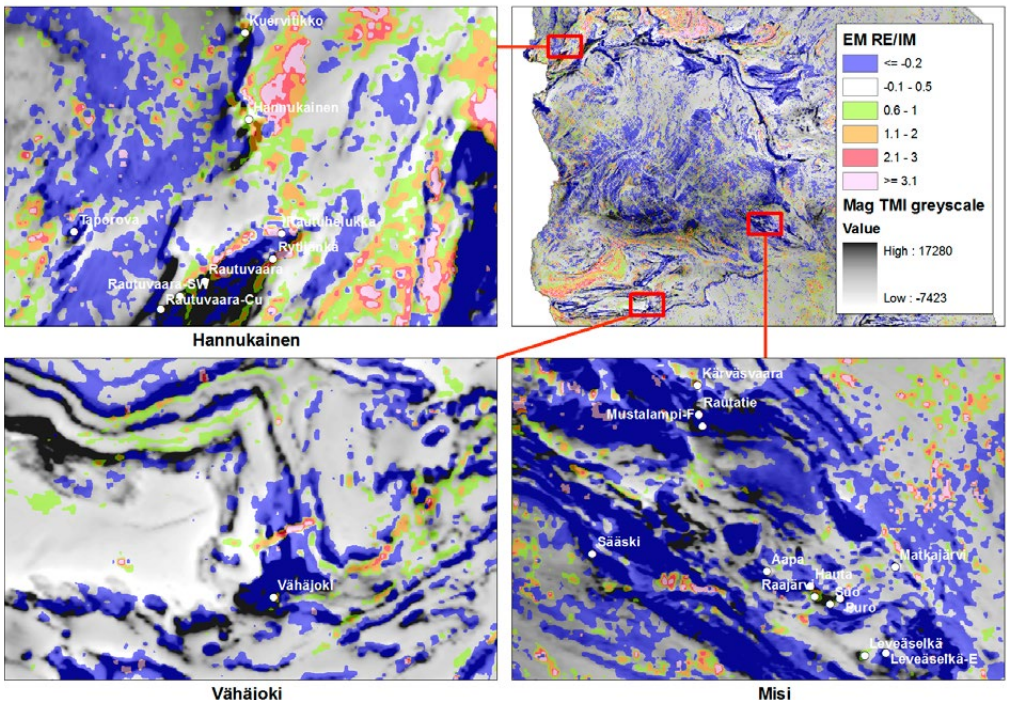
D. At low conductivities the electromagnetic low frequency response is negative. IP = In phase (real) component; Q = Quadrature (imaginary) component. μ_r = magnetic permeability. From: Leväniemi et al. 2009.

The example area is 30 km wide.

Insert 5.
Method for magnetic anomaly detection by classifying magnetic anomalies (H. Leväniemi, GTK in Airo et al. 2014). Upper right: schist belts surrounding the Central Lapland granitoid area. Three more detailed example maps: Hannukainen (upper left), Vähäjoki (lower left) and Misi (lower right).

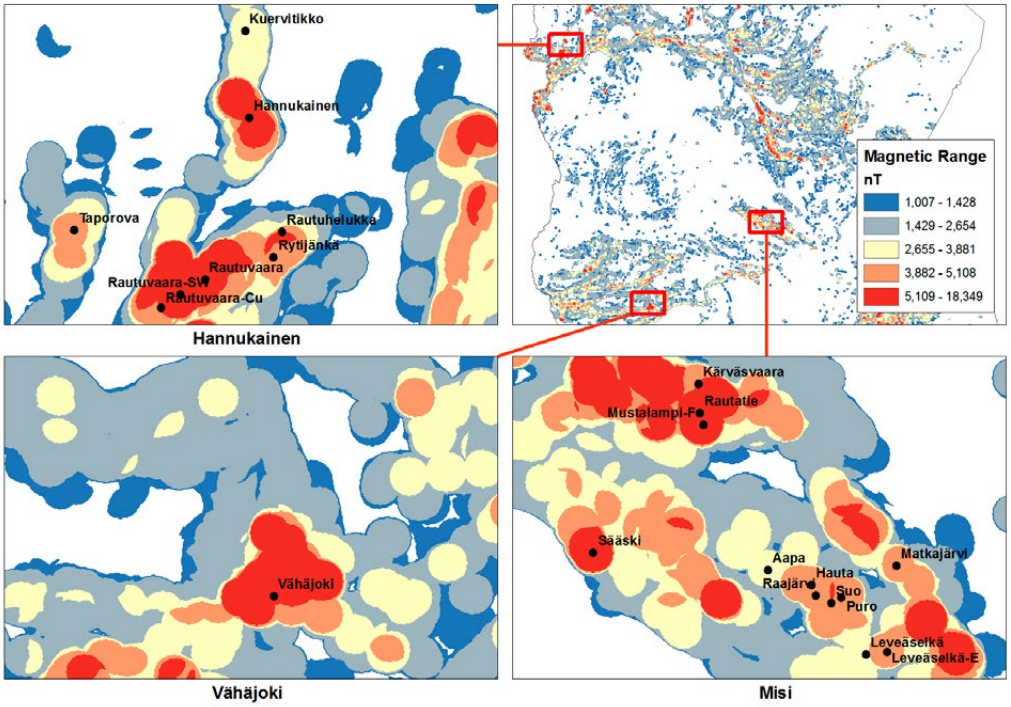


Thematic classification of magnetic total field intensity. TMI = Total Magnetic Intensity in 5 categories. Red and pink indicate the highest magnetic anomaly intensity.



Classification of electromagnetic data: the ratios of Real to Imaginary components (Re/Im).
The upper limit of magnetically susceptive range was set Re/Im = -0.2. Blue indicates low Re/Im ratios (negative values of the real component) and express the so-called magnetite-effect. Red and pink indicate good electrical conductivity. Before classification the data were smoothly filtered (3-point median filter) in order to remove point-distortion due to low original measurement values.

Insert 5 (cont)



Magnetic anomaly detection.
The method is based on the variation of the magnetic anomaly amplitude (minimum → maximum value) in a circular region at each data cell. The analysed data set comprised aeromagnetic data of 50 m grid cell size. The radius of the moving window was as large as 750 m to ensure an adequate spatial extent of the anomalies.

MINERAL DEPOSIT TYPES

Ore deposit types addressed in this review

Ore deposits can be classified on the basis of the metals they contain, the form of the deposit (i.e. mineral distribution), ore associations (associated host rocks or geological structures), or the genesis of the deposit (processes or controls) (McQueen 2005). For the overview of the geophysical signatures of mineral deposit types, the genetic classification works better than classification based only on metals, because most metals have quite comparable physical properties and are not therefore always distinguishable. The genetic classification of ore deposits presented in Eilu & Lahtinen (2013) is applied in this review for the geophysical characterization (*Table 8).*

More than 30 different genetic types of metal deposits have been encountered in Finland (Eilu et al. 2012, FODD 2013). The most significant types of these, on the basis of past production and present resources, are classified into five main groups. In the following, the discussion of geophysical properties is focused on these five main groups, with critical minerals discussed in the sixth group:

1. Magmatic Ni-Cu, PGE
2. Intrusion-hosted V-Fe-Ti, Cr
3. Orogenic gold
4. Volcanogenic Massive Sulphides (VMS) (Cu, Zn, Pb, Au, Ag)
5. Banded iron formations and IOCG-style Fe±Cu, Au
6. Porphyry Cu-Au
7. High-tech metals and uranium

Genetic classification schemes incorporate elements of composition, forms and association. From these, it is possible to construct predictive models that can be used to search geological environments in which appropriate ore-forming processes have probably operated (McQueen 2005).

The major metallogenic epochs can be related to global geodynamic processes, including major periods of crustal break-up and convergence. Accordingly, in Fennoscandia, the metallogenic events and diagnostic mineralization systems can be related to specific plate tectonic settings (Lahtinen et al. 2012, Eilu & Lahtinen 2013, Weihed et al. 2008). Concerning geophysics, the recognition and outlining of tectonic plates and major structural zones controlling mineralization requires analysis of regional geophysical data suites covering vast areas.

In this Special Paper volume, the review of physical properties of ore deposit types or mineralization styles is mainly based on published information, in particular on the key note speeches and presentations that were given at two geosciences conferences: Exploration07 held in Toronto in 2007 (proceedings by Milkereit (ed.) 2007), and the SGA meeting held in Uppsala in 2013 (proceedings by Johnsson et al. (eds.) 2013).

General petrophysical properties

The physical properties of different mineral systems basically depend on the concentration, texture and properties of petrophysically anomalous minerals and properties of the host rock. The most important anomalous minerals are iron sulphides and iron oxides. In some cases, the ore minerals

Table 8. Genetic classification of the main ore deposit types (mineralization styles) in Finland and selected example deposits. The classification is inspired by metallogenic areas by Eilu et al. (2012) (see indices in the first column). The examples include both metallogenic belts and individual deposits.

METALLOGENIC AREA	MINERALISATION STYLE	EXAMPLES
	ARCHEAN	
F032, F047	Komatiitic Ni(-Cu-PGE)	Kuhmo-Suomussalmi Ni, Ruossakero (Ni,Co)
F032	Epithermal or VMS Ag-Zn	Taivaljärvi Ag-Zn
F030	BIF	Ilomantsi Fe (Huhus)
F023	Orogenic gold	Ilomantsi Au (Pampalo)
F034	Epithermal gold	Oijärvi (Au,Ag)
PALEOPROTEROZOIC RIFTING STAGES OF THE ARCHEAN CONTINENTS		
F035, F045	Layered intrusion Cr	Kemi Cr, Koitelainen Cr, Akanvaara Cr
F036	Mafic intrusion-hosted V-Ti-Fe	Mustavaara V
F035	Layered intrusion PGE ± Ni-Cu	Suhanko PGE, Siika-Kämä PGE
F048	Ultramafic-mafic intrusion Cr, Ni-Cu ± PGE	Sattasvaara Ni, Kevitsa Ni, Sakatti Ni
F031	Alkaline intrusion V-Ti-Fe	Otanmäki V
F029	Black shale –hosted Ni-Zn-Cu- Co	Talvivaara Ni
F038	SEDEX	Haukipudas (Zn,Cu)
F037	Volcanic red-bed Cu	Peräpohja Cu
F021, F020	VMS (Cu-Zn±Co)	Hammaslahti (Cu-Zn), Outokumpu (Keretti)
F039	Skarn Fe	Misi
PALEOPROTEROZOIC SUBDUCTION-RELATED		
F028, F004, F009	VMS (Zn-Cu, Au-Cu)	Vihanti-Pyhäsalmi, Häme (Zn,Cu), Haveri (Tampere Au,Cu)
F004	Porphyry Cu ± Au	Kopsa, Kedonojankulma (Au, Cu)
F009	Epithermal Cu ± Au	Kutemajärvi (Tampere Au,Cu)
PALEOPROTEROZOIC COLLISIONAL		
S034, F037	IOCG (Au, Cu-Au, Fe)	Pajala-Kolari, Vähäjoki
F020	Outokumpu-type Ni	Vuonos
F043, F040	Orogenic gold (Au±Cu,Co,Ni)	Kittilä (Au,Cu), Kuusamo (Co-Au ±Cu ±U± LREE)
F004, F007	Orogenic gold (Au±Cu)	Satulinmäki (Au), Jokisivu (Au)
F016, F027, F006	Mafic-ultramafic intrusion Ni-Cu	Kotalahti (Ni,Co), Hitura (Ni,Co), Vammala (Ni,Co,Cu)
F005, F024, F002	Rare metal pegmatite Sn, Nb-Ta, Li-Be	Somero Li, Emmes Li, Kemiö (Ta,Be)
PHANEROZOIC		
R013	Peralkaline intrusion, Carbonatite	Sokli Apatite-Nb-REE

themselves do not possess properties that are detectable, or their concentration may be too low to have a geophysical influence, but there may be some properties of altered host rock that may indirectly be used in targeting mineralization.

Magnetite and pyrrhotite, or other ferrimagnetic minerals, tend to accumulate in ore deposits (including the non-iron ones) or in their environments. Because these minerals often accompany economic mineralization in various ways, their magnetic properties can be important in the search for ore deposits, even though they do not often represent the economic minerals (Hrouda et al. 2009).

Sulphide deposits occur in rock complexes that were metamorphosed from zeolite to granulite facies and underwent regional metamorphism together with surrounding rocks. During the process of metamorphism, the ores may have recrystallized and partially mobilized together with quartz, carbonates and barite (Hrouda et al. 2009). New minerals may have formed, for example, pyrite, pyrrhotite, magnetite, and Mg- and Fe-carbonates. The most commonly documented ore mineral-related reaction in metamorphosed deposits is an increase in the pyrrhotite/pyrite ratio with increasing metamorphic grade. The transformation can often also be reversed, mostly in the terminal phase of regional metamorphism when new pyrite is created. The reaction of pyrite to produce pyrrhotite in metamorphosed massive sulphide deposits is considered unlikely, and much of the data indicate that the pyrite-pyrrhotite conversion is equivocal. Pyrrhotite can also occur in the form of a hexagonal phase, which is antiferromagnetic and displays only relatively low susceptibility. This pyrrhotite can occur in the deeper parts of massive sulphide ores, whereas a mixture of hexagonal and monoclinic pyrrhotite is typical of the near-surface parts.

Petrophyscial properties determine which geophysical techniques can best be used to investigate a mineral system. A comprehensive collection of geophysical properties for different mineralization styles is available in literature and has been presented by several authors in the proceedings of Exploration 07 (Milkereit (ed.) 2007). They are summarized below to act as background for the following sections:

- **Densities** are largely controlled by the iron content in most rocks and minerals. Iron oxides and sulphides may be identified as gravity anomalies, but so also may dense host rocks such as mafic/ultramafic rocks.
- **Magnetism** readily distinguishes deposits bearing magnetite (Fe-Ti-V ores, iron oxides) or ferrimagnetic pyrrhotite (massive sulphide deposits). Remanent magnetization may have a prevalent role.
- **Remanent magnetism** can cause great difficulties in modelling, especially with automated methods. Disseminated pyrrhotite with relatively low susceptibilities can have Q-values (Q = the ratio of remanent to induced magnetism) over 10, producing significant local anomalies.
- **Electrical conductivity** can usually be used to discriminate between base metal sulphides and Fe oxides. Some ore-related minerals may also have high conductivities. In general, iron oxides or certain rock types such as mafic or ultramafic rocks are not highly conductive.
- **Radioactivity** may have some role in limited cases. Generally, felsic or intermediate rocks may have high radioactivity, whereas mafic and ultramafic rocks and Fe and base-metal sulphides have little or no natural radioactivity. Thorium (Th) tends to enrich in alkaline rocks. It forms complex ions with, for example, sulphides, carbonates and phosphates. Chemical alteration may produce some identifiable change. Uranium (U) is generally highly mobile, leaving thorium behind. Carbonatization may result in enrichment of U and Th, together with Au. Potassic alteration produces increased potassium radiation values, even for mafic and ultramafic rocks.
- **Seismicity** has an important role in structural and lithological mapping. Seismic methods are able to produce high-resolution images of the geological structure and to define sharp boundaries in the subsurface. Seismic imaging techniques require the input of information regarding propagation velocities of the media. This information is usually recovered from seismic data by interactive velocity analysis, or such information can be obtained from borehole acoustic logs. The interpreted boundaries can be used as constraints in the inversion of other methods such as magnetics and gravity, which can be used to fill volumes with physical property values but have poor resolution at depth.
- **Anomalous in most physical properties** are sulphide deposits. These typically include

pyrrhotite, pentlandite and chalcopyrite, which may be the reason for electrical conductivity, chargeability, density, magnetic susceptibility, natural radioactivity and acoustic velocity. This combination of physical properties makes the detection of significant concentrations of sulphides fairly straightforward. Sulphides easily deform plastically so that their hosting structures may be easily identified by geophysical methods.

The petrophysical database of GTK contains laboratory measurement results for various ore deposit types. These are summarized in *Table 9*. The number of samples is annually increasing as new measurements are performed to serve the needs of different GTK projects. The naming of the old database samples is quite generalized and sketchy, but nevertheless the measurement values give an idea of the properties. To complement the ore sample database, new measurements were carried out for this study. The new samples were selected from GTK's rock museum archives to cover different types of ore deposit, and they represent selected ore types from old Finnish mining areas. The new measurements are compiled in *Table 10*, and in addition to density and magnetic properties, they also include electrical properties.

Insert 6 compares the petrophysical properties of various ore deposit types in GTK's petrophysical database and the new measurements for this study (H. Säävuori, GTK), and they display great variation in properties, of course depending on the ore mineral content and type. The overall impression is that remanence is important, as indicated by Q-ratios of >1 for most of the samples.

Spatial distribution of ore deposits

Structural and metamorphic aspects, in addition to geophysical properties, have an important role in affecting the assessment and the type of mineralization. The metamorphic and alteration history of the host rock and the age and timing of mineralization are important, but of ultimate importance is the structural control – at a large or small scale, or both. Mineralization may be related to craton margins or crustal block boundaries, the mineralization may need contrasting redox conditions that may be found at lithological contacts, the fluid propagation needs fault systems or weakness zones formed by regional folding, or the mineralization may favour a certain type of pressure release such as in fold hinges.

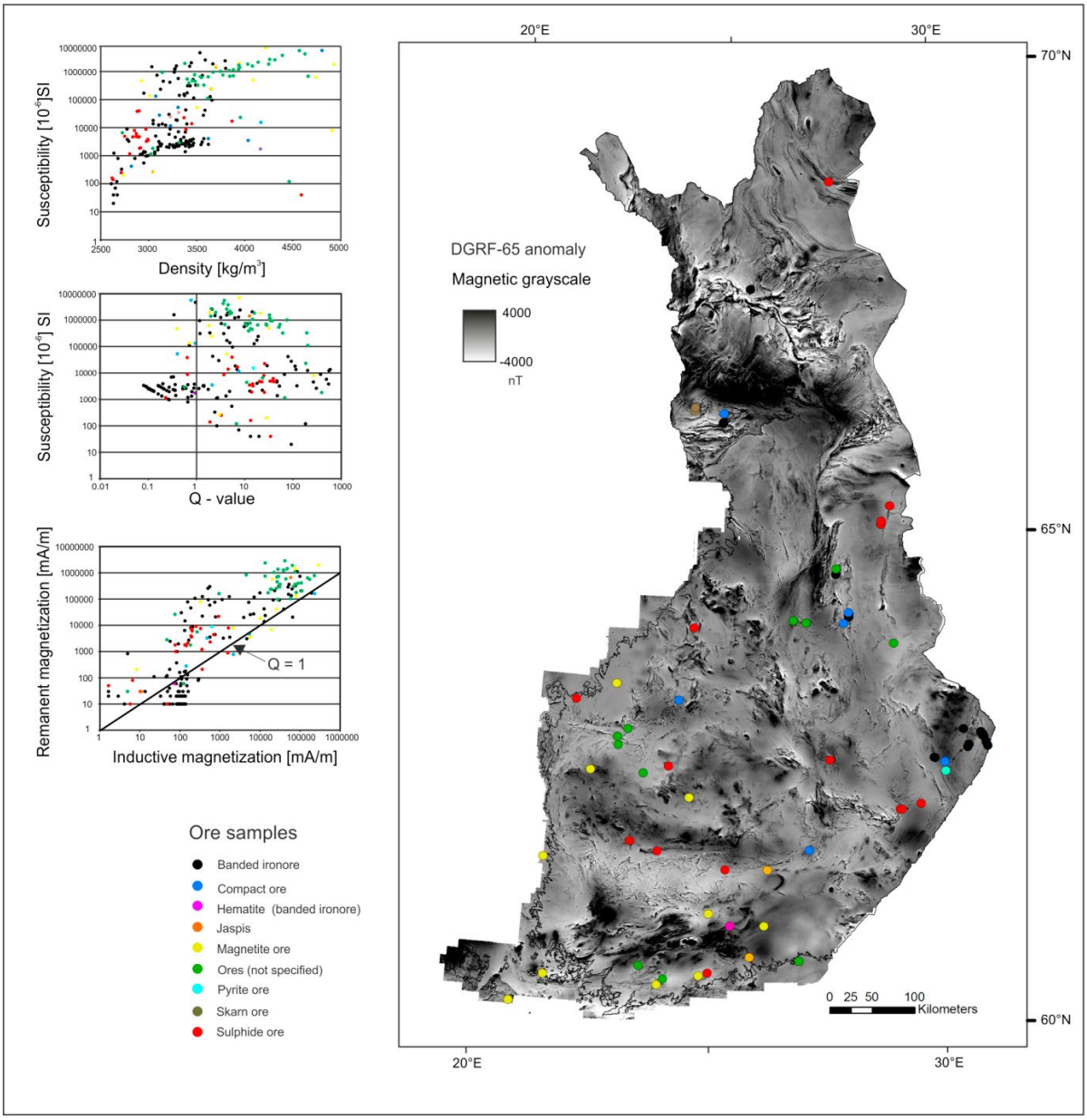
Insert 7 summarizes structural lineaments in Finland and adjacent areas, as inferred from Bouguer and magnetic anomaly data. Most mineral deposits are spatially related to these structural unconformities. The lineaments were interpreted at more detailed scale on the basis of processed magnetic and gravity gradient data sets. Major structural zones are indicated in potential field data as parallel or aligned gradient zones following a certain orientation and referring to great unconformity. Frequently, they are associated with a linear change in the overall regional anomaly amplitude. Regional gravity data reveal more prominent and crustal-scale structural features, whereas magnetic anomalies for the most part describe the surface. The major lines traverse from Sweden to Russia and crosscut the whole of Finland. Their main orientations are linked to the main periods of crustal break down in the history of the Fennoscandian shield. *Insert 8* displays the Bouguer anomaly map with the interpreted major structural lines. The map shows regions of regional high gravity that can be related to granulite facies metamorphism, e.g. the Archaean eastern Finland and the granulite belt in Lapland. Granulite facies metamorphic units close to the surface tend to be associated with regional gravity highs, because prograde metamorphic processes increase the content of higher-density mafic silicates in rocks. Block boundaries and major unconformities are outlined by regional gravity lows. One of them is the Raahe-Laatokka zone, with local gravity highs following both sides of the zone. Of the areas with known Ni deposits, Kotalahti (also *Insert 10*) and the Vihanti-Pyhäsalmi area are related to gravity highs.

Insert 9 displays the magnetic anomaly map of Finland with the classification of magnetic anomalies (techniques and colour categories are explained in Insert 5). Magnetic anomaly classification distinguishes the high magnetic anomaly amplitudes, either due to magnetite or monoclinic pyrrhotite. In addition to high magnetic susceptibilities, these anomalies are affected by high remanent magnetization. These techniques are a useful way of detecting iron formations, e.g. BIF, Fe-bearing cherts or

the Fe deposits associated with IOCGs. Some distinctive magnetic anomalies in Finland that stand out are outlined: the Sulkavanniemi-Kitee anomalies in southeastern Finland (A), the Vittinki zones on the west coast (B), Kuusamo schist belt (C) and the Kellojärvi ultramafic body in the southern part of the Kuhmo greenstone belt.

Insert 6.
Comparison of various ore deposit types in the petrophysical database and the new measurements of rock museum archives made for this study (H. Säävuori, GTK). Sampling sites are shown the aeromagneticmap.

Samples from database
Individual information of petrophysical parameters in Table 9. The group "Ores (not specified)" is petrophysically quite homogeneous and probably is composed of the same type having distinctive magnetic properties.
Petrophysical diagrams:
1. Susceptibility versus density; sulphide ores have here generally lower densities than e.g., banded iron ores.
2. Susceptibility versus Q-ratio; line Q = 1 is shown. Q >1 denotes the overall fine magnetic grain size for all except banded iron ores.
3. Remanent versus induced magnetization; line Q = 1 is shown. Remanent magnetization predominates over the induced (Q >1) for all other samples except banded iron ores.



Insert 6 (cont)

Samples from rock museum
Individual information of petrophysical parameters in Table 10. The metallogenic areas by Eilu et al. (2012) are indicated for comparison.
Petrophysical diagrams:
1. Susceptibility versus density quite scattered.
2. Remanent versus induced magnetization; on both sides of line Q =1.
3. Susceptibility versus resistivity: quite scattered and 6 samples have resistivity out of the measurement range.

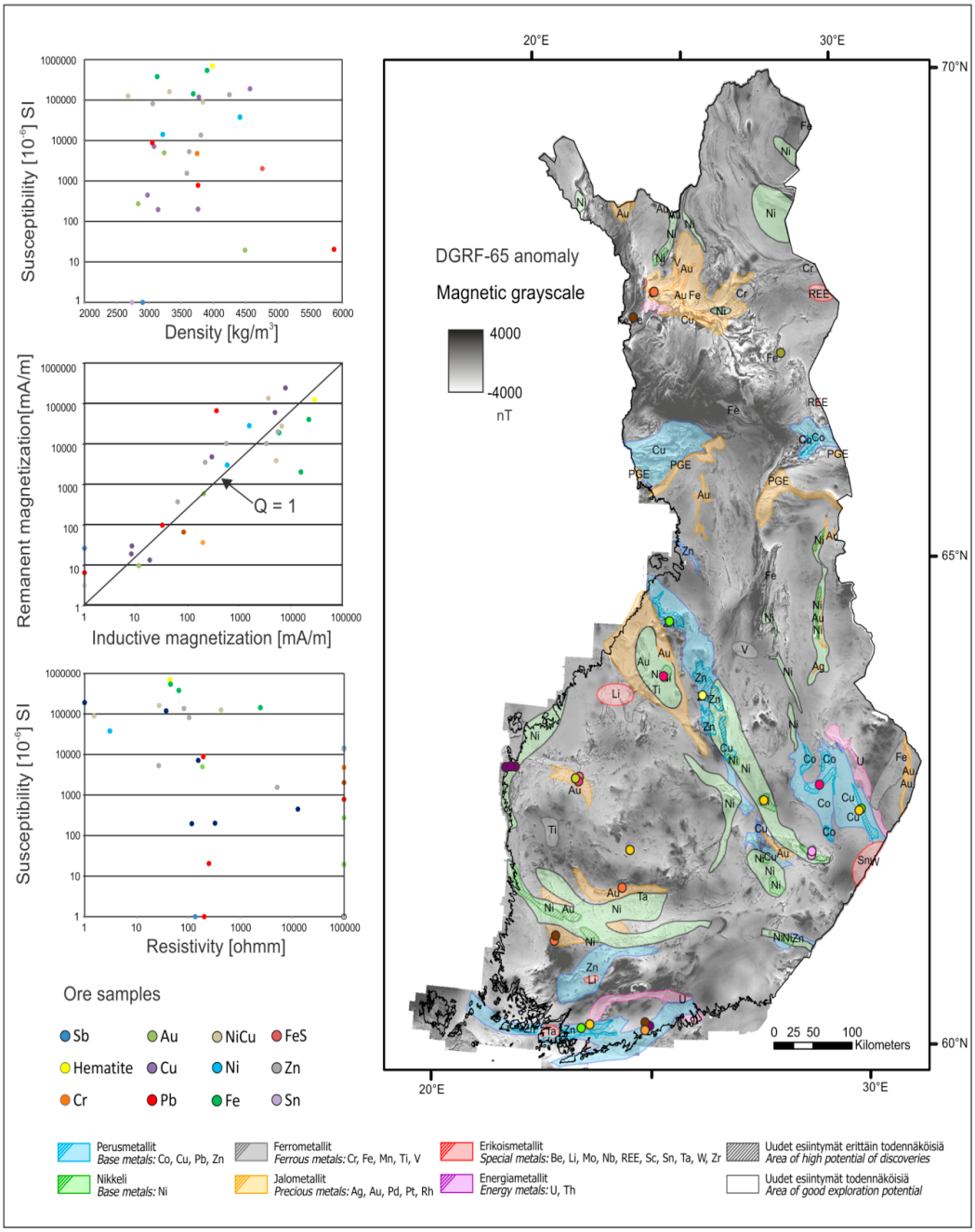


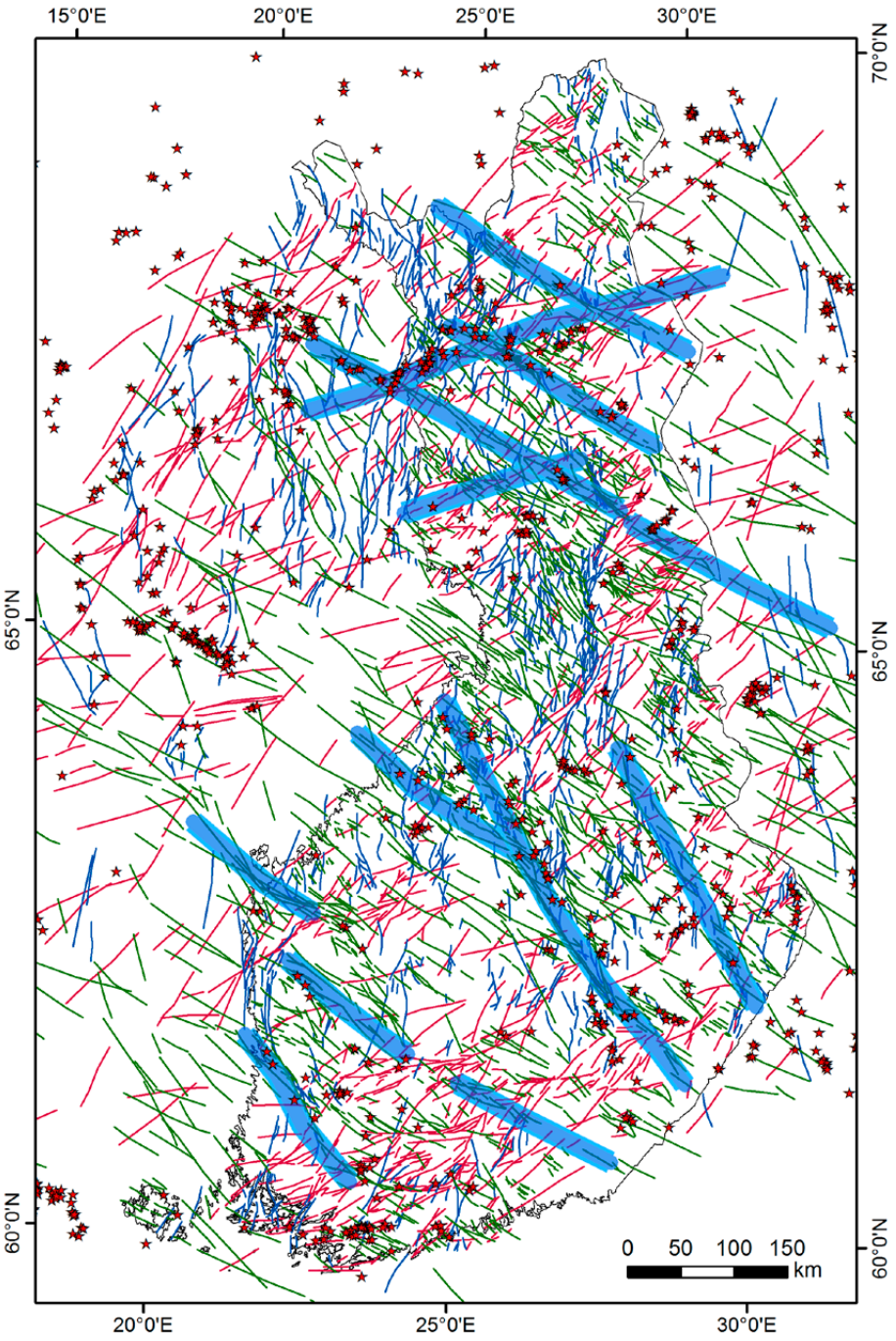
Table 9. Petrophysical data from ore samples measured at GTK. Averages of petrophysical properties. Density g/cm^3, susceptibility $\cdot 10^{-6}$, remanent magnetization Am$\cdot 10^{-3}$, Q-value (Königsberger ratio), magnetite content calculated.

Ore deposit type	Density	Magnetic susc.	Remanent magn.	Q-value	Magnetite content	N
BANDED IRONORE	3244	238668	56153	41	8	125
COMPACT ORE	3499	735880	34212	2	2	8
HEMATITE (BANDED IRONORE)	4163	1740	60	1	0	1
JASPIS	3371	710350	332375	8	29	2
MAGNETITE ORE	3877	1166924	391160	33	21	11
ORES (not specified)	3860	1145132	647151	43	34	40
PYRITE ORE	4168	15360	8810	15	1	1
SKARN ORE	3269	29440			1	2
SULPHIDE ORE	3032	8300	3816	17	0	25
Total	3386	448774	187277	36	12	215

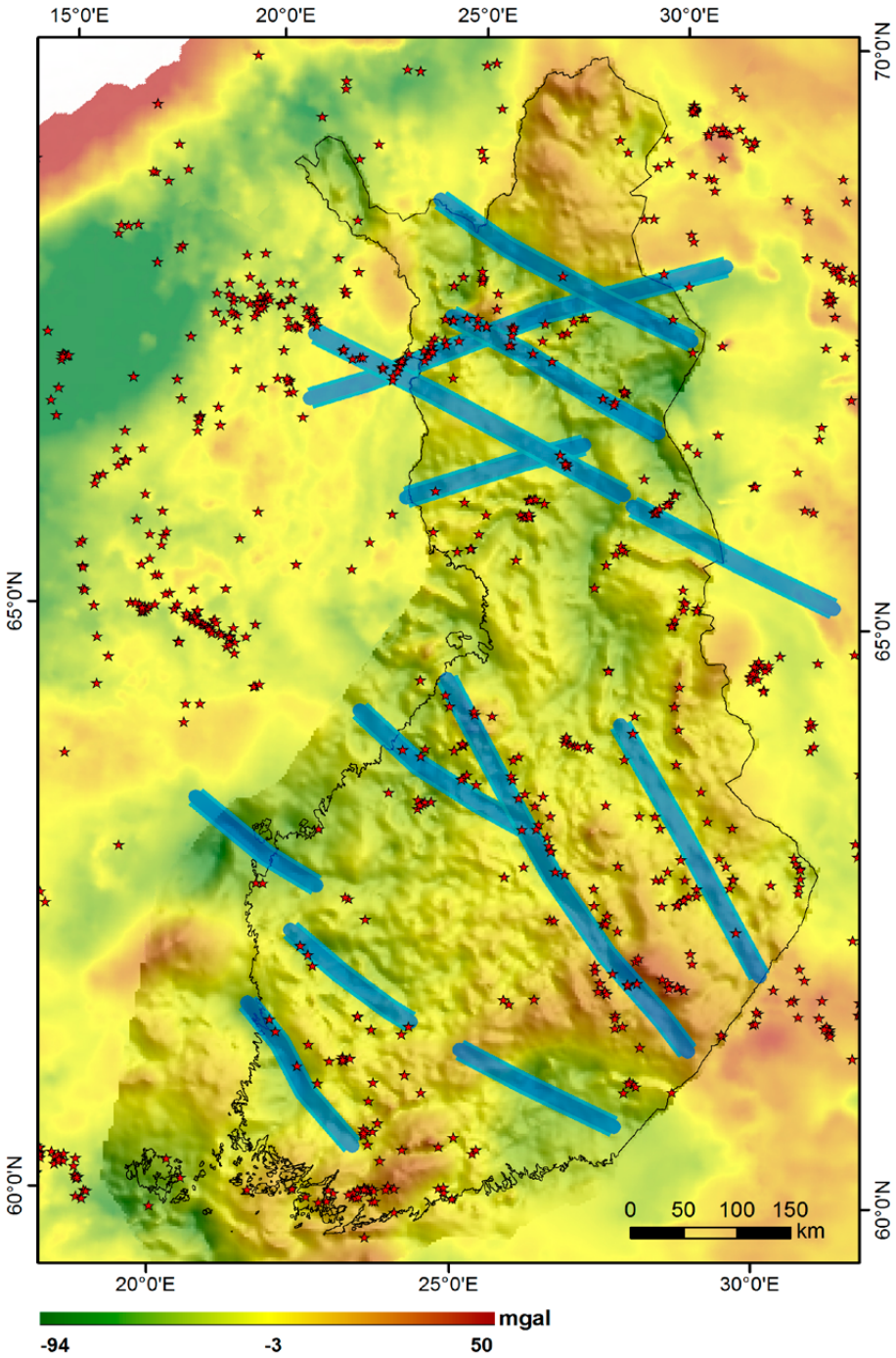
Table 10. Petrophysical data for ore samples from rock museum archives of GTK. Averages of petrophysical properties. D = density g/cm^3, K = magnetic susceptibility $\cdot 10^{-6}$, J = the intensity of remanent magnetization Am$\cdot 10^{-3}$, Q-value (Königsberger ratio), R = resistivity Ohms, and 6 = conductivity (S/m).

Ore type	Metal	Sampling site	D(kg/m^3)	K(10^{-6}SI)	J(mA/m)	R(ohmm)	σ (S/m)	Q-ratio
ANTIMONY ORE	Sb	KALLIOSALO	2903	-5	25	136	0,007	
HEMATITE	Fe	TAPOROVA	3984	698953	119279	44	0,023	4,16
CHROME ORE	Cr	AKANVAARA	3747	4781	35			0,18
GOLD ORE	Au	SAATTOPORA	3236	4972	558	186	0,005	2,74
GOLD ORE	Au	ORIVESI	4489	19	17			21,14
GOLD ORE	Au	JOKISIVU	2833	274	9			0,83
COPPER ORE	Cu	ORIJÄRVI	3774	119185	57592	37	0,027	11,79
COPPER ORE	Cu	ORIJÄRVI	3079	7147	4583	155	0,006	15,65
COPPER ORE	Cu	KERETTI	3761	202	29	326	0,003	3,45
COPPER ORE	Cu	TYNYSNIEMI	3142	197	18	116	0,009	2,25
COPPER ORE	Cu	HAMMAS-LAHTI	2978	449	13	12909	0,000	0,70
COPPER ORE	Cu	OUTOKUMPU	4566	190384	232736	1	1,471	29,83
LEAD ORE	Pb	PAKILA	3052	8792	63578	194	0,005	176,44
LEAD ORE	Pb	METSÄ-MONTTU	3761	784	93			2,90
LEAD ORE	Pb	KORSNÄS	6118	1	6	202	0,005	255,58
LEAD ORE	Pb	KORSNÄS	5869	20	13	249	0,004	15,85
Ni-Cu-ORE	Ni-Cu	KOTALAHTI	3836	88891	129846	2	0,658	35,64
Ni-Cu-ORE	Ni-Cu	PETOLAHTI	3319	161175	26507	27	0,03651	4,01
Ni-Cu-ORE	Ni-Cu	HITURA	2677	125950	3697	426	0,00235	0,72
NICKEL ORE	Ni	LAUKUN-KANGAS	4411	37944	27116	3	0,32680	17,44
NICKEL ORE	Ni	HÄLVÄLÄ	3213	14162	2873			4,95
IRON ORE	Fe	BÖLE	3128	379479	1932	65	0,01530	0,12
IRON ORE	Fe	SUSIMÄKI	3901	540796	38739	45	0,02208	1,75
IRON ORE	Fe	SUUOJA	3687	142900	18198	2445	0,00041	3,11
PYRITE ORE	FeS	PYHÄSALMI	4758	2027	63			0,76
ZINK ORE	Zn	HAMMAS-LAHTI	3625	5307	3357	27	0,03729	15,44
ZINK ORE	Zn	PAKILA	3588	1553	353	5153	0,00019	5,54
ZINK ORE	Zn	VIHANTI	4247	135891	19110	82	0,01216	3,43
ZINK ORE	Zn	VIHANTI	3059	81476	9835	103	0,00968	2,95
ZINK ORE	Zn	ORIJÄRVI	3805	13619	9828			17,61
TIN ORE	Sn	PERÄLÄ DIKE	2739	0	3			1836,10

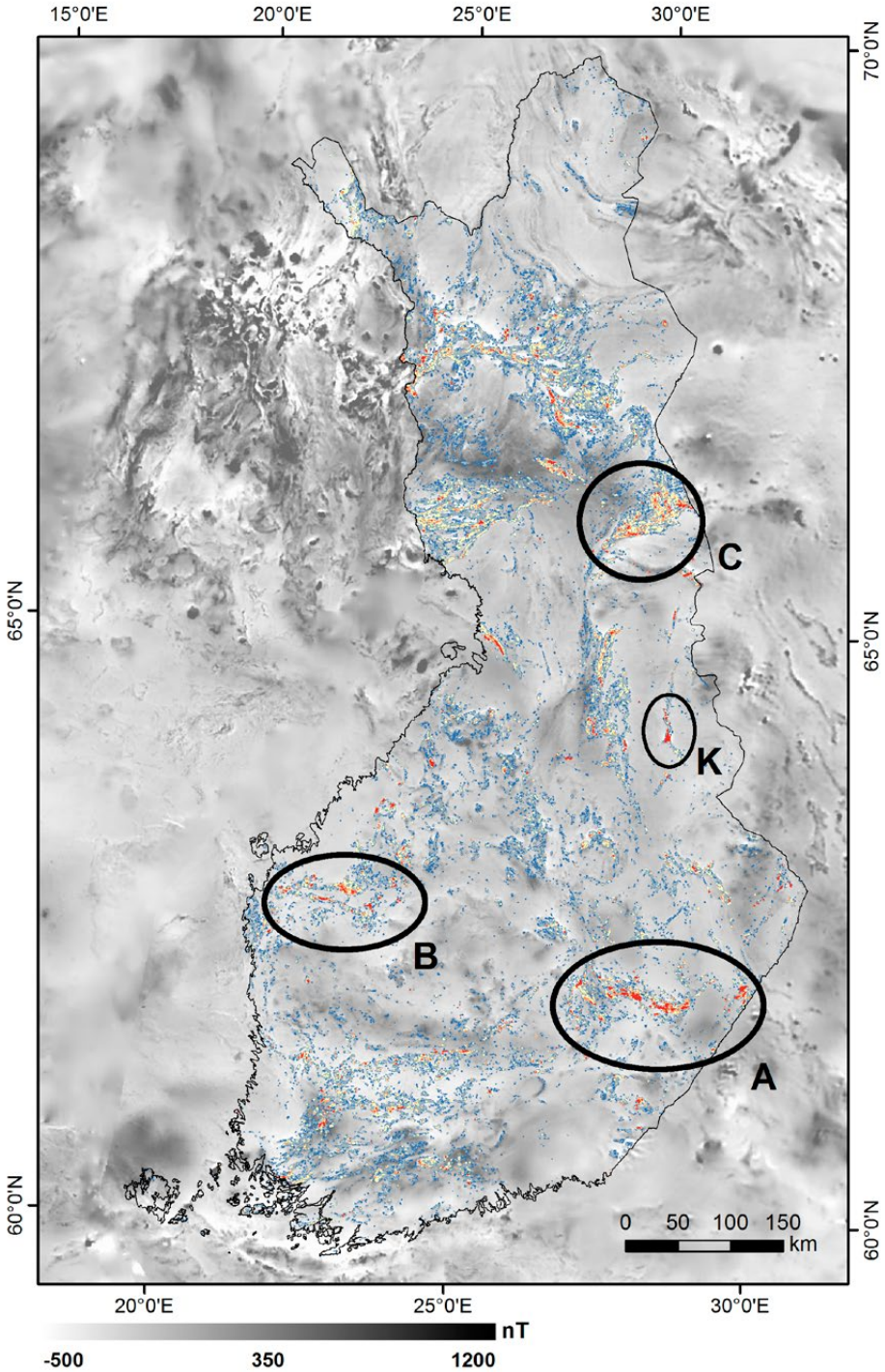
Insert 7.
Structural lineaments inferred from potential field data (Airo, M.-L., GTK 2013). Three main orientations are indicated by green, blue and purple lines. Ore deposits (FODD 2013) are spatially related to the structural zones.



Insert 8.
Bouguer anomaly map of Finland and adjacent areas. The main interpreted structural zones (as in Insert 7) follow crustal scale lineaments in gravity data. Mineral deposits (FODD 2013) are spatially related to the structural zones.Bouguer anomaly map of Fennoscandia based on Korhonen et al. 2002.



Insert 9.
Aeromagnetic anomaly map with classified magnetic anomalies. The techniques and colour categories are explained in Insert 5.The outlined regions with prominent magnetic anomaly intensities are discussed in the text. Magnetic anomaly map of the Fennoscandian Shield based on Korhonen et al. 2002.



MINERAL SYSTEMS: GEOPHYSICAL MANIFESTATIONS

Magmatic Ni-Cu, PGE

Ni-Cu sulphides are frequently magnetic but not always, and they may produce a wide variety of geophysical signatures. Despite the association of magnetic anomalies with many nickel sulphide ore bodies, magnetic data alone are unreliable for locating ore bodies, and the use of other geophysical methods, particularly electromagnetic, is essential for target selection (Gunn & Dentith 1997). The physical properties of PGE (platinum group element) minerals are not usually apparent because of their low concentrations. Common characteristics of Ni-Cu sulphides, including magmatic or sulphidic mineralization, can include magnetic high signatures, density and gravity highs, and/or either electrical conductivity (due to the presence of massive sulphides) or chargeability (due to disseminated sulphides), magnetic susceptibility, natural radioactivity, and acoustic velocity (Lightfoot 2007, King 2007).

Geophysically, the most relevant mineral among Ni-Cu sulphides is pyrrhotite. It is dense, highly magnetic in its monoclinic form, and electrically conductive. The hexagonal form of pyrrhotite is antiferromagnetic and may display only relatively low susceptibility. Pyrrhotite and magnetite are present in the Co, Ni and PGE deposits, and the measurement of magnetic susceptibility from drill cores is a good addition to susceptibility well logging. The susceptibility measurement of cores also helps in searching for the relationship between ferrimagnetic minerals and economic ore minerals and/or footwall rocks. The magnetic susceptibility can also be used in the selection of samples for more detailed laboratory study.

The known Finnish magmatic nickel deposits have been classified into three types (Rasilainen et al. 2012):

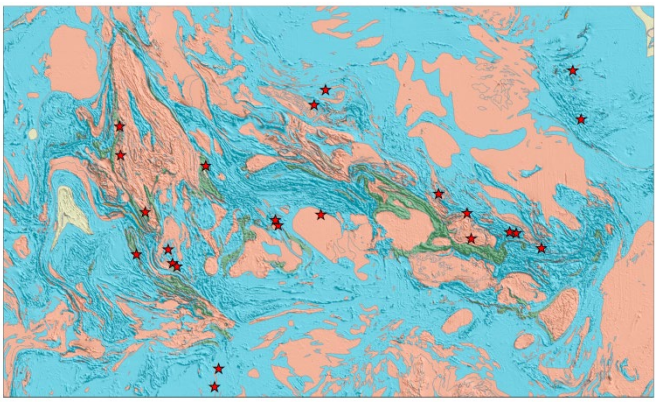
1) Ni-Cu deposits associated with synorogenic Palaeoproterozoic (~1.89–1.87 Ga) mafic-ultramafic intrusions in central and southern Finland,
2) Ni-Cu deposits associated with Archaean (~2.8 Ga) komatiitic rocks in eastern and northern Finland and Palaeoproterozoic (~2.05 Ga) komatiitic rocks in northern Finland, and
3) Ni-Cu-PGE deposits associated with Palaeoproterozoic (~2.45 Ga) mafic-ultramafic layered intrusions in northern Finland.

The two large nickel deposits, Kevitsa Ni-Cu-PGE deposit and Talvivaara Ni-Zn-Cu-Co deposit, represent rare Ni deposit types, and are not included into the classes above.

Most of the important nickel deposits worldwide are located along craton margins, which are commonly associated with prominent gravity and also magnetic signatures. Good examples are Kotalahti-Sulkavanniemi occurrences located on the eastern side of the regional gravity low indicating the Raahe-Laatokka zone (*Insert 10*). Magmatic Ni-Cu and Ni-Cu-PGM deposits are associated with mafic-ultramafic rocks, which themselves produce strong magnetic and gravity anomalies. However, deposits of *type 1* are hosted by weakly magnetic mafic-ultramafic intrusives. The komatiitic host rocks (*type 2*) in general are highly magnetic on the basis of their magnetite content, as are the mafic-ultramafic layered intrusions (*type 3*). On closer inspection, *type 3* intrusions are associated with variable magnetic signatures, depending on the alteration of magnetite-bearing units. The PGE deposits in the Suhanko-Siikakämä and Koillismaa areas are related to the weakly magnetic parts of layered intrusions. Zientek (2012) reviews the geophysical characteristics of contact-type Cu-Ni-PGE and Reef-type PGE deposits. The main issue is that geophysical methods do not map PGE minerals directly, but they indicate physical property contrasts of primarily sulphide minerals and magnetite that may be associated with mineralization.

- Detailed aeromagnetic surveys may be used to establish a geologic framework of an area, but do not generally give a direct indication of mineralized rock. High-resolution surveys can be used to map igneous layering and tectonic structures, particularly if the data are enhanced to distinguish subtle features.
- Gravity studies may be used to determine the subsurface extent of rocks with variable density, and they are particularly well suited to mapping and modelling the extent and volume of

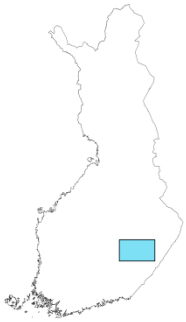
Insert 10.
The Sulkavanniemi-Savonlinna belt in southeastern Finland is associated with intensive magnetic anomalies.

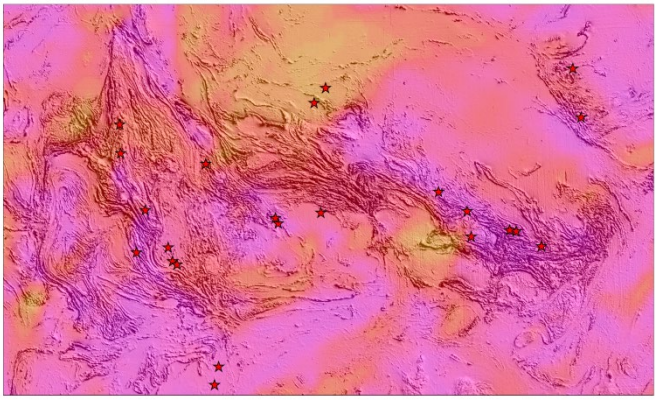


Mineral deposits are from FODD (2013).

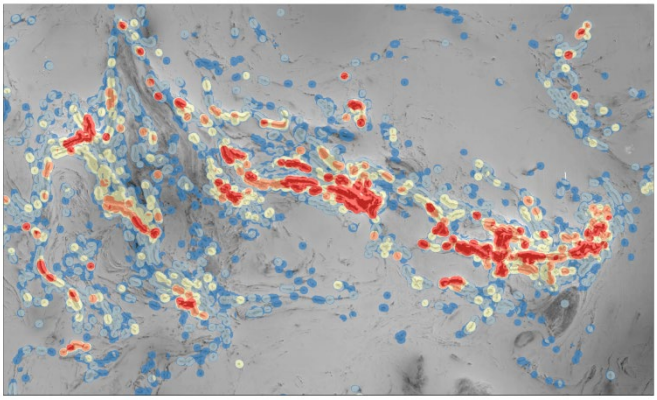
The geological map is based on the GTK in-house digital bedrock database (Geological Survey of Finland 2010).

The map area is 130 km wide.

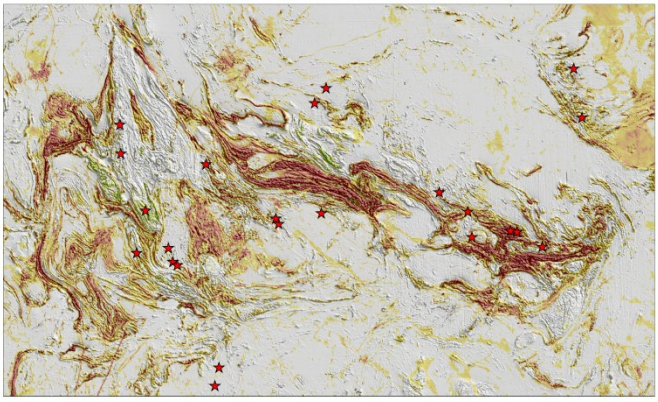




High intensity short wave-length magnetic anomalies along the block boundary that is indicated by gravity data.



Highest magnetic anomaly amplitudes are related to the schists (not volcanic rocks).



High intensity magnetic anomalies are associated with coincident conductivity, so the magnetism is carried by abundant monoclinic pyrrhotite.

Red = good conductivity
Green = magnetite

mafic and ultramafic igneous rocks. However, gravity measurements are not used to directly locate mineralized rocks.

- Electrical methods work best on rocks that are conductive. For contact-type deposits, airborne and ground electromagnetics and induced polarization surveys can be used to identify and delineate rocks that contain conductive and interconnected net-textured or massive sulphide ores. For reef-type ores, with low sulphide mineral contents, electrical responses are subtle.
- Once a rock layer that contains reef-type mineralization has been identified, seismic studies can be used to map the subsurface extent of the rocks. Three-dimensional seismic surveys have been used to identify structural features such as faults, depressions and cavities.

Three examples, in Figures 4–5 and Insert 10, show how magnetite-bearing komatiitic rocks can be distinguished by the classification of airborne magnetic and electromagnetic (frequency-domain) data.

A negative AEM response meaning non-conductivity characterizes the host rocks of Lomalampi, Kevitsa and Sakatti Cu-Ni-PGE occurrences in northern Finland (Fig. 4). However, on closer inspection, in Kevitsa the major part of the intrusion is recognized as conductive due to pyrrhotite as the main magnetic mineral. The magnetic anomaly classification enhances magnetic signatures associated with relevant remanence. The Sakatti anomaly stands out locally in the detailed image.

Petrophysical properties for the komatiite-hosted Lomalampi PGE-Ni-Cu-Au deposit in northern

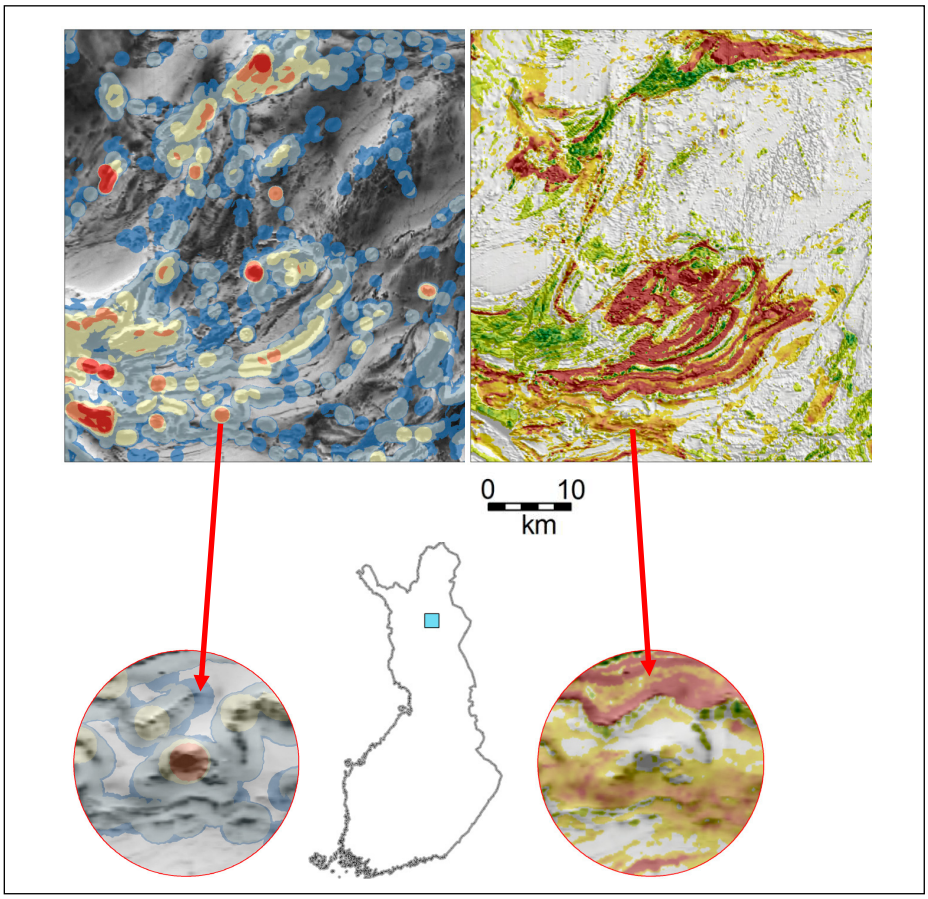


Fig. 4. Airborne geophysical integrated maps from northern Finland covering the Koitelainen gabbro and adjacent areas. The upper images are 50 km wide. Rounded circles below show detail of the Sakatti occurrence.
Upper left: Aeromagnetic anomaly classification map. This classification points out magnetic anomalies of very high intensity and short wavelength (red circles; see more detailed explanation and colour categories in Insert 5). Sakatti and some other similar targets can be noticed.
Upper right: Airborne electromagnetic (AEM) classification; background magnetic derivative map. AEM categories are explained in Insert 4; good conductivity is indicated in red and poor/no conductivity in green. The magnetite-bearing komatiitic rocks stand out as resistive. The electrical conductors are related to greenstones with a graphite-bearing interlayer or the sheeted dyke complex.
Circles below: The Sakatti formation is associated with a magnetic anomaly (left), but not with electrical resistivity or conductivity (right).

Finland have been summarized by Salmirinne (2010), in Figure 5. Various rock groups can easily be classified in the density/susceptibility plot. Peridotites hosting the mineralization have the highest susceptibilities, whereas sulphide schists have lower susceptibilities but higher densities.

The Sulkavanniemi-Savonlinna belt in southeastern Finland is associated with highly intensive magnetic anomalies (Insert 10). These are related to volcanic rocks and black schists, and the magnetic zone continues to Kitee, close to the Russian boarder.

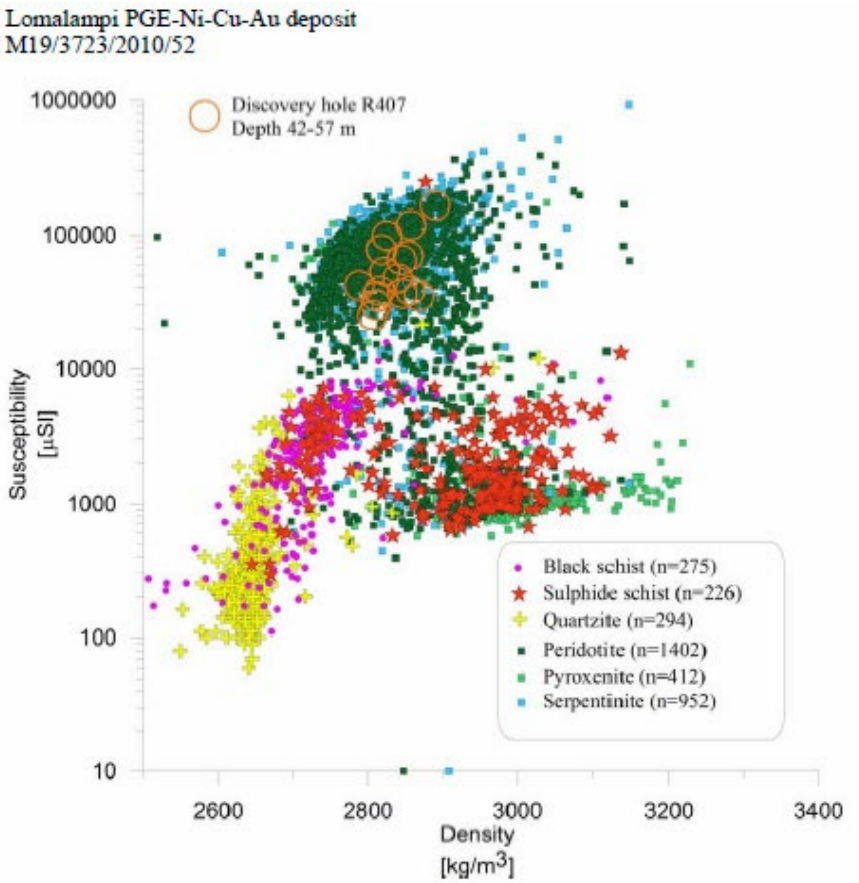


Fig. 5. Petrophysical properties from Lomalampi (Salmirinne 2010). Diverse rock types are clustered into typical density/susceptibility ranges. Serpentinites and peridotites have the highest susceptibilities. The mineralized peridotites (orange circles) cannot be distinguished from other peridotites by their density/ susceptibility distributions. Black schists and sulphide schists are clustered into one group with pyrrhotite susceptibility and density < 2800 kg/m^3, but sulphide schists also form another cluster with a higher density range.

Table representing petrophysical properties: Median values of petrophysical in-situ loggings for the main rock types reported from drill holes in the Lomalampi area (8 drill holes, 2004). Note the low level of radioactivity of ultramafic rocks.

Rocktype	Count	Density [kg/m3]	Susceptibility [µSI]	Chargeability [%]	App. Resistivity [Ωm]	Tot. Radiation [µR/h]
Graywacke	631	2588	293	2.85	4686	3.23
Felsic tuffite	165	2742	732	5.69	69	7.39
Graphite schist	92	2796	855	1.24	371	0.50
Graphite-sulphide schist	605	2707	2790	7.65	21	18.54
Gabbro	102	3082	1801	1.79	2019	6.21
Peridotite	1320	2810	60861	3.19	6153	0.57
Pyroxenite	589	2993	5346	1.47	5022	0.87
Ultramafic hyalotuffite	914	2920	934	0.88	835	1.06
Ultramafic lava	387	3027	1170	1.32	2784	3.72

Geophysical key factors for Ni-Cu-PGEs

Density
The density of sulphide minerals is generally anomalously high, generally >4 g/cm^3. Mafic and ultramafic rocks hosting Ni-Cu-PGE deposits also have high densities because of the elevated abundance of mafic minerals such as olivine and pyroxene. Thus, density may be used for the direct detection and quantitative measurement of many sulphide ores.

Gravity
Regional airborne gravity (or regional ground gravity with fair resolution) and gravity gradiometer coverage would be one of the best ways to promote nickel sulphide (and other) exploration. Gravity is an effective technique for defining the geometry and structure of the deposits and their host rocks at a regional scale.

Magnetic susceptibility
Ni-Cu sulphides may be magnetic, but not always. The economic sulphides pentlandite and chalcopyrite are non-magnetic, whereas the magnetic properties of many sulphide ores are dominated by pyrrhotite. The latter is moderately magnetic in its monoclinic form but non-magnetic in its hexagonal form. The mafic and ultramafic host rocks may be highly magnetic, depending on the concentration of magnetite, which is a common primary mineral or a hydrothermal alteration product. However, depending on the degree of serpentinization, their magnetization may be very variable.

Electrical properties: conductivity/resistivity
Electrical conductivity is the most effective single tool in the identification of semi-massive to massive Ni-Cu sulphides. There is a very large contrast (about 8–9 orders of magnitude) between the electrical properties of Ni-Cu sulphides and their host rocks. Pyrrhotite has one of the highest conductivities: only graphite is of the same order or higher, but graphite rarely occurs in a truly massive crystalline form over large thicknesses, i.e. tens of metres thick. This makes massive to semi-massive pyrrhotite-dominated bodies, with or without nickel sulphides, fairly unique in conductance (conductivity x thickness).

Electrical chargeability
Since the Ni-Cu-S minerals all have high metallic conductivity, they have high electrical chargeability. The good contrast with most host rocks makes them good induced polarization (IP) targets. Chargeability may be a good indicator of vein-type deposits or unconnected disseminated sulphides which are rarely conductive. If country rocks have too similar properties to the exploration target, the application may be complicated. Both barren and nickelferous sulphides are conductive and chargeable – as are carbonaceous shales and graphite (i.e. black shales in Finland). In the case of low levels of sulphides, disseminated magnetite in mafic to ultramafic rocks can cause chargeability anomalies.

Natural radioactivity
Radiometric data have been acquired on a regional basis comparable in scale to magnetics in many countries and in Finland as well. The anomalously low radioactivity of mafic and ultramafic rocks makes radiometrics a very valuable tool in areas where surface soils have weathered in place. The almost non-existence of U, K and Th in massive Ni-Cu-S also makes natural radiometrics a potentially useful passive radioactive method for identifying massive sulphides (through the absence of a response).

Seismics
Density plays an equal part with acoustic velocity in the acoustic reflectivity coefficient. This is an important factor in hard rock seismics, where velocity variations can be small and density values dominate the reflectivity. Seismic reflection is the only method in which spatial resolution does not decline rapidly with depth and has the capability to directly detect deposits at depths that are many multiples of their size. However, due to non-uniqueness in simple reflection images, these signatures may not be definitive.

Ketola (1982) evaluated the applicability of exploration methods in the search for Ni-Cu ores in Finland, the emphasis being on those methods that contributed to the discovery of known ore deposits. The report describes the geology, geophysics and petrophysics of most of the Ni-Cu ore deposits found at that time in Finland. Geophysical surveys play a key role in the search for Ni-Cu ores associated with mafic and ultramafic rocks. The large number of magnetic and electromagnetic anomalies in areas with pyrrhotite-bearing black schists has made it increasingly necessary to use geochemical surveys for classifying geophysical anomalies. The detectability of an ore-potential mafic intrusion depends not only on its dimensions and attitude, but also on its grade of serpentinization, which is reflected in the variation of the petrophysical properties. The main point is how well an anomaly produced by a certain method can be distinguished from the environment.

The summary of geophysical key properties in the following fact sheet is mainly after King (2007) and Lightfoot (2007).

Intrusion hosted Fe-Ti-V, Cr

Magmatic rocks containing economic concentrations of iron, titanium, vanadium and phosphorous are commonly associated with massif-type anorthosites and related rocks. Aeromagnetic surveying is an essential geophysical tool for the exploration of Fe–Ti–V–P ore bodies, because these deposits contain ferrimagnetic Fe-Ti oxides. The gravity method is also utilized, because of the high density minerals. The magnetic properties of Fe–Ti ore deposits present contrasting signatures, depending whether the natural remanent magnetization is dominated by hemo-ilmenite or multi-domain magnetite (Charlier et al. 2015). Characterization of the rock magnetic properties in the Rogaland Anorthosite Province led McEnroe et al. (2001) to distinguish between two groups of Fe–Ti mineralization types that produce large and contrasting anomalies on aeromagnetic maps, a classification that can be extended to Fe–Ti oxide deposits worldwide. Bolle et al. (2014) also suggested anisotropy of magnetic susceptibility (AMS) analysis for studying the structural details of folding and stretching of a layered intrusion.

Magnetic properties of Fe-Ti deposits

The first group of Fe–Ti occurrences encompasses noritic rocks with relatively abundant coarse (multi-domain) magnetite and homogeneous (near-end-member) ilmenite. Ores from this group have high values of natural remanent magnetization (NRM) and magnetic susceptibility (K), coupled with low values of coercivity and Koenigsberger ratios (Q, the ratio of NRM to induced magnetization, i.e. K multiplied by the ambient magnetic field). They produce an induced-current magnetic response parallel to the Earth's present-day magnetic field, giving rise to positive anomalies on aeromagnetic maps. The magnetic properties of these rocks are dominated by magnetite; in particular, the viscous NRM behaviour is "more or less as predicted from the common behavior of multi-domain magnetite".

The second group of Fe–Ti deposits, with a magnetic signature drastically different from the former group, includes hemo-ilmenite rich noritic rocks and massive hemo-ilmenite ores, containing no or minor multi-domain magnetite. Rocks from this group have high NRM and Q values, and moderate to high coercivities and susceptibilities. They produce remanence-influenced to remanence-dominated anomalies, and are thus strongly dependent on the orientation of the Earth's magnetic field at the time of emplacement and cooling. The strong and stable NRM of this group primarily results from hemo-ilmenite; however, oxide exsolutions in silicates, chiefly exsolved blades and rods of hemo-ilmenite and/or magnetite with ilmenite oxy-exsolution in pyroxenes, may contribute significantly to NRM in some cases.

from *McEnroe et al. 2001*

Intrusion-hosted Fe mineralization types in Finland include mafic intrusion-hosted (Mustavaara) and alkaline intrusion-hosted (Otanmäki) V-Fe-Ti ore deposits. These are associated with strong magnetic responses. The Koivusaarenneva metallogenic zone contains ilmenite-rich gabbro intrusions and magnetite-bearing gabbros: magnetic and gravity anomalies have been used in their definition. The Koitelainen Cr, V, PGE deposits, associated with a mafic to ultramafic weakly magnetic layered intrusion, include two sulphide-free, PGE-enriched chromite reefs and a V-rich gabbro (Mutanen 1997).

The Misi Fe-deposits contain martitizied magnetite (Saltikoff et al. 2006, Niiranen et al. 2003). When magnetite is gradually replaced with martite (hematite), the effective magnetic grain size of magnetite decreases, resulting in an increased intensity of remanent magnetization, and this in turn is reflected in the magnetic anomaly signature. The magnetite destruction associated with magnetite oxidation and deep weathering to hematite is directly measurable as decreased magnetic susceptibility, and finally it may be that the iron ore deposits form clear magnetic lows.

The example Otanmäki V-Fe-Ti area (metallogenic zone F031 in Eilu et al. 2012) is characterized as follows (Fig. 6):

- magmatic vanadium-rich magnetite-ilmenite deposits in deformed and metamorphosed gabbros;

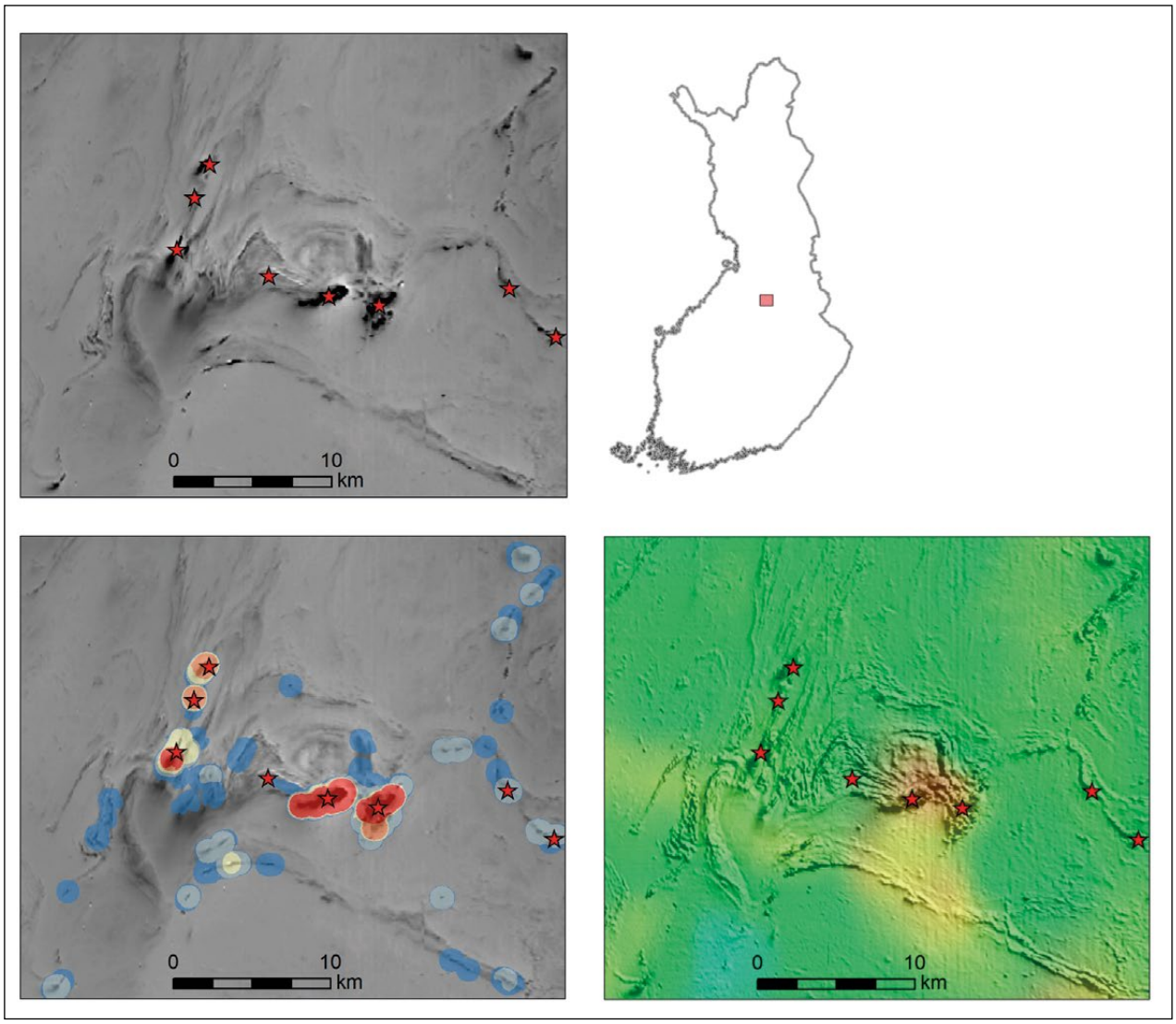


Fig. 6. The Otanmäki V-Fe-Ti area comprises local magnetic anomalies located along a regional gravity gradient zone (lower right). The outline of detailed maps is 40 km wide. Upper left: aeromagnetic map; lower left: magnetic anomaly classification with the magnetic derivative map as background. Mineral deposits from FODD (2013).

- in addition to ferrous metals, a potential source of REE, Zr and Nb in gneissic alkaline granitoids;
- Proterozoic rocks inside Archaean gneisses;
- introduce a local gravity anomaly north of the regional gravity gradient zone;
- magnetite-bearing units are distinguished by electromagnetic data.

Orogenic gold

Most of the gold in Fennoscandia is produced from orogenic gold deposits with gold as the main product. Orogenic gold deposits occur throughout the Palaeoproterozoic of southern and central Finland. However, a number of gold deposits may alternatively be classified as volcanogenic massive sulphides (VMS) or iron oxide-copper-gold (IOCG) or porphyry copper deposits, where gold is the by-product. These categories will be discussed separately later in this article. The undiscovered resources in orogenic gold deposits in Finland have recently been assessed by Eilu et al. (2015).

The physical properties of gold (Au), with a density of 19 300 kg/m3 and an electrical conductivity of 5·107 S/m, are one of the most anomalous of all elements. However, gold occurs in such low concentrations that it does not give any direct geophysical response, although the influences of geological processes that result in gold deposition may be detectable. A key element is to understand and detect the different types of gold deposits and their favourable geologic settings and controls at regional to local scales, especially in covered terrains (Robert et al. 2007, Hoover et al. 1995).

Orogenic gold deposits

These have occasionally formed from the Mesoarchaean to younger Precambrian and during the whole Phanerozoic eon. Orogenic gold occurrences are associated with processes involving the flow of sulphur-bearing hydrothermal fluids transferring a considerable amount of the leachable gold through major fault networks and along migration paths. Eventually, gold precipitates in secondary and tertiary fault zones in shallow areas of uplifting orogens (Goldfarb et al. 2001, Groves et al. 1998). Three main types of orogenic deposits are distinguished based on their host-rock environment: greenstone-hosted, turbidite-hosted, and BIF-hosted types. The dominant sulphide mineral is pyrite at greenschist grade and pyrrhotite at amphibolite grade. Ore bodies are surrounded by zoned carbonate-sericite-pyrite alteration haloes that are variably developed depending on the host rock composition. The ore bodies are associated with quartz veins, brittle faults, brittle–ductile shear zones and some strongly ductile shear zones. In greenstone belts, the significant vein deposits are typically distributed along specific regional compressional to transpressional structures (Robert et al. 2007).

Geophysically relevant minerals in gold deposits are pyrite, pyrrhotite and magnetite. The dominant sulphide mineral in metamorphic rocks is commonly pyrite at greenschist grade and pyrrhotite at amphibolite grade. At a regional scale, the majority of deposits are spatially associated with regional shear zones and commonly occur in greenschist to lower-amphibolite grade rocks, consistent with the overall brittle-ductile nature of their host structures. Alteration characteristics for orogenic gold deposits include Fe-Mg-carbonate alteration associated with magnetite destruction. The structural control of mineralization is characterized by fault or shear zones, especially with bends and intersections or culminations of anticlines, high-angle reverse faults or cross-structures. EM methods can also be used to map alteration, lithological contacts and faults. Regional potassium highs in radiometric data may indicate felsic magmatism, and local potassium highs with low Th/K may be associated with potassic alteration. For Au-quartz vein deposits, IP methods and gamma-ray spectrometry may be applied to map massive quartz veins (resistivity highs) and potassic alteration (potassium highs, respectively). Regional gravity lows over thick volcanic sequences or local gravity highs associated with felsic intrusions may indicate alteration.

Geophysical key factors or methods for gold deposits

Petrophysical data
These may be collected via borehole logging or hand sample analysis. Density, magnetic susceptibility, resistivity, chargeability and gamma radiation may be good indicators, depending on the contrast in physical properties of the mineralized and the unaltered country rocks. Petrophysical data have also been used at the regional scale, for example, to look at the effects of metamorphism on the geometry and geophysical response of greenstone belts.

Gravity methods
These are used at all scales from the identification of prospective gold districts to that of gold-related hydrothermal alteration at a local scale (from airborne gravity gradient systems to deposit-scale ground gravity). At a regional scale, gravity is an effective technique for defining the geometry and structure of greenstones belts. The structure and alteration can also be mapped.

Magnetic method
This provides information on geological units, faults, and shear and alteration zones that may control the mineralization. Magnetite destruction due to chemical alteration can be outlined from magnetic lows.

Radiometric data
These work well in defining chemically altered rock units if the alteration has introduced significant amounts of potassium, as is typical for orogenic gold systems. Uranium is generally mobile, leaving thorium behind.

Electric or electromagnetic methods
These are effective if sulphides are included. The conductive and chargeable sulphides are commonly associated with orogenic gold. Airborne electromagnetic methods reveal the geological framework or delineate zones of high conductivity within resistive mafic to ultramafic host rocks. The methods most successfully applied for gold exploration have been DC resistivity and induced polarization (IP). Other important electromagnetic methods used are VLF-R, SP and HLEM. Electromagnetic anomalies are caused by graphite, sulphides and fractures containing water. IP may detect disseminated sulphides and SP is used to map and classify conductive sulphide and graphite occurrences.

Seismic surveys
These are not widely applied in gold exploration. This is largely due to the complicated 3D geometry of lithological contacts and their often steeply dipping nature. In recent years, seismic surveys have nevertheless been used at local and regional scales to map the stratigraphy and structure in the appropriate geological settings.

Remote sensing
Very significant technological advances have been made in the last ten years in the field of infrared spectroscopy for alteration mapping. Satellite multispectral systems such as ASTER and airborne hyperspectral sensors such as Hymap have improved spatial and spectral resolution, higher signal-to-noise ratios, and wider spectral range coverage. Field portable hyperspectral instruments such as Pima have become standard tools for alteration mapping since they were first introduced to the mineral industry in the mid-1990s (Robert et al. 2007).

Archaean greenstone belts hosting orogenic gold in Finland are Tuntsa, Oijärvi, Suomussalmi, Kuhmo, Tipasjärvi and Hattu belt (Eilu et al. 2015, Airo 2007, Airo & Mertanen 2008). The magnetic anomalies of greenstones are generally of low intensity because of the deficiency of magnetite in greenstone grade mafic rocks. The effect of hydrothermal alteration on the petrophysical properties of ultramafic units in the Kittilä greenstone belt are described in *Insert 11*.

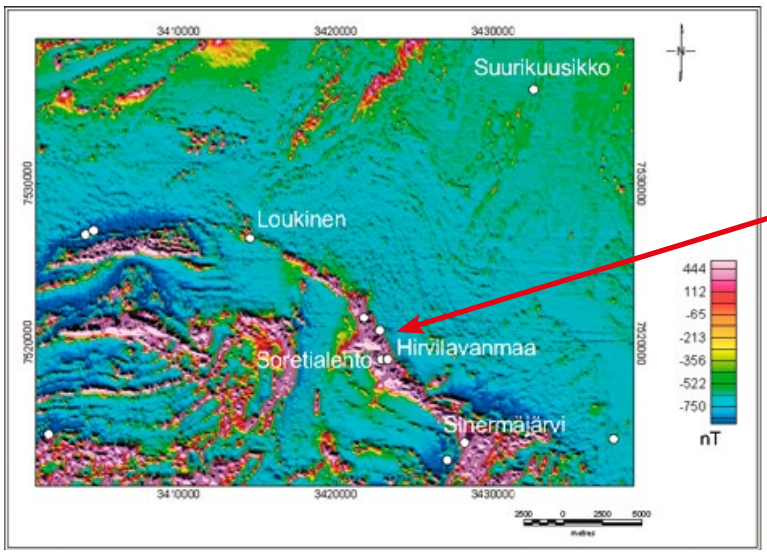
The Palaeoproterozoic Kittilä greenstones host several orogenic gold deposits (Eilu et al. 2015). The Kittilä and Salla greenstone belts, and Kuusamo and Peräpohja schist belts are all characterized by weakly magnetic host rocks. Petrophysical properties have been widely used in selecting the best methods for ground surveys in gold prospects of the Kittilä greenstone belt. For example, Salmirinne and Turunen (2006) reported detailed petrophysical investigations from Kaaresselkä and Loukinen. Results based on 24 drill hole sections below the ground water table displayed the difference between gold-bearing mylonites and other rocks. In the apparent resistivity and gamma radiation results, there were satisfactory differences between the two classes, but in the density, susceptibility and chargeability measurements, the distributions of the parameter values overlap too much for practical use in field exploration. The use of gamma radiation is insignificant in field mapping, as the radiation attenuates to zero within 30 cm of the source. However, in drill hole logging, the gamma radiation can be used to detect the potassic alteration zones that are commonly related to gold mineralization. Electrical and electromagnetic methods were best suited to gold exploration in the Kaaresselkä area. Results from Loukinen were based on 15 drillhole sections and showed a significant difference in chargeability between gold-bearing and other rocks. Another clear difference was in gamma radiation. Although the logged chargeability appears to be a very good parameter, the presence of black schists makes its use difficult in practice. There is incompatibility between the histograms of apparent resistivity and chargeability. It is not clear how the gold mineralization is related to black schists and sulphides, which can be detected with electrical methods regardless of the gold content. The chargeability works in much the same way, but is affected by polarization effects. For some reason, possibly mineralogical or structural, mineralized rocks polarize more than barren rocks. The overall result is that the induced polarization may be effective as a ground survey method, and gamma radiation in the logging environment.

The Palaeoproterozoic Svecofennian Häme and Pirkkala belts in southern Finland are highly prospective for gold (metallogenic zones F004, F007, F009 by Eilu et al. 2012). Insert 12 provides a regional overview of the geophysical data for this area, which is characterized by magnetic anomalies coinciding with conductivity anomalies. The magnetic and electrical signature is due to monoclinic pyrrhotite, which is the main ferrimagnetic mineral in this area. It also carries high remanent magnetization, which is why these anomalies are distinguishable. A regional gravity high is associated with migmatites, indicating a high metamorphic degree (also noted by Hölttä, unpublished information on metamorphic zones in Finland). Petrophysical properties produce mappable criteria for separating mineralized source rocks and barren intrusions (Mertanen & Karell, *p. 89*). Different rock types are clearly distinguished by their petrophysical properties.

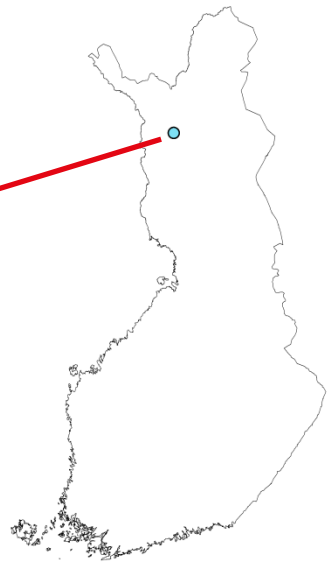
Volcanogenic Massive Sulphides (VMS) (Cu, Zn, Pb, Au, Ag)

Volcanogenic massive sulphide (VMS) deposits are significant sources of Zn, Cu and Ag, Au and other metals. The most common sulphide mineral in VMS deposits is pyrite, which is often associated with other sulphides such as pyrrhotite, chalcopyrite, sphalerite and galena (Morgan 2012). Magnetite and hematite may also be associated. This combination of geophysically relevant minerals indicates that the VMS deposits are anomalous in most physical properties, including electrical conductivity, chargeability, density, magnetic susceptibility, natural radioactivity and acoustic velocity.

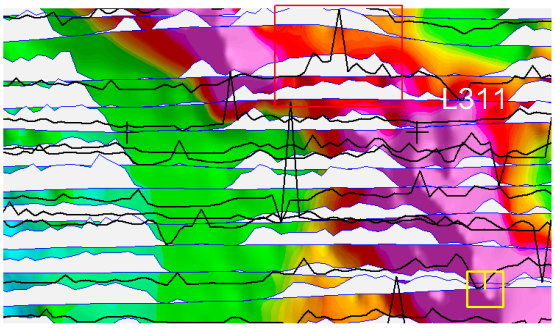
Insert 11.
Effect of hydrothermal alteration on gold-potential ultramafic rocks at Kettukuusikko site in northern Finland (Airo 2007).



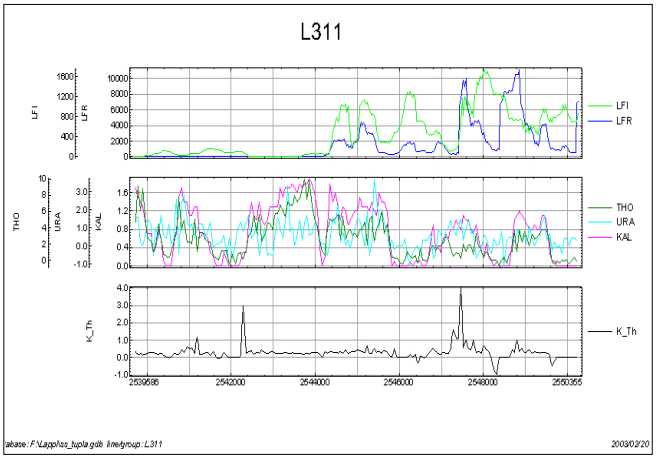
Aeromagnetic map showing highly magnetic ultramafic rocks at the southern boundary of Kittilä greenstones. Known gold occurrences are indicated.



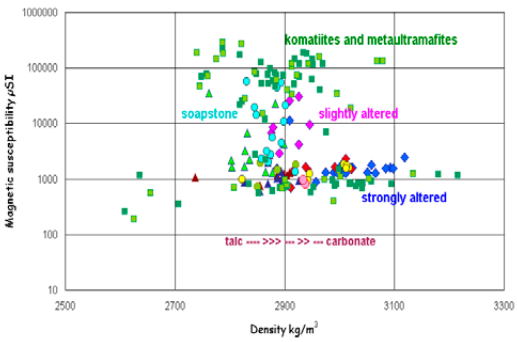
Kettukuusikko site.



Detail of the Kettukuusikko site. Aeromagnetic grid + Potassium radiation profiles along survey lines. Line 311 is displayed as detailed panel on the right side.



Electromagnetic (upper profiles) and radiometric (in the middle) data along flight line 311. K/Th (below) peaks at the contact of altered ultramafic unit and graphite-bearing volcanogenic schists.

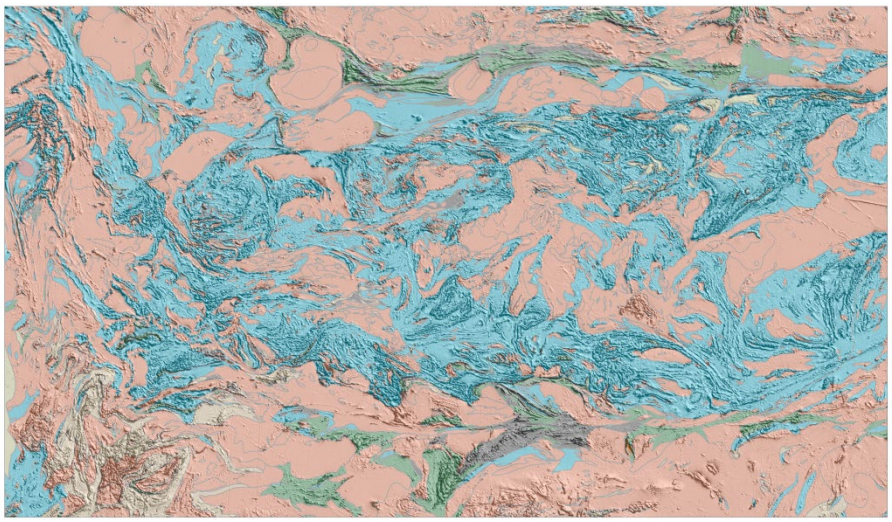


Talc-Carbonate alteration in the ultramafic unit: Decrease in magnetic susceptibility because of the destruction of magnetite. Densities grow because the released iron is incorporated with silicates and iron-bearing carbonates.

Characteristics of orogenic gold mineralisation in ultramafic rocks :

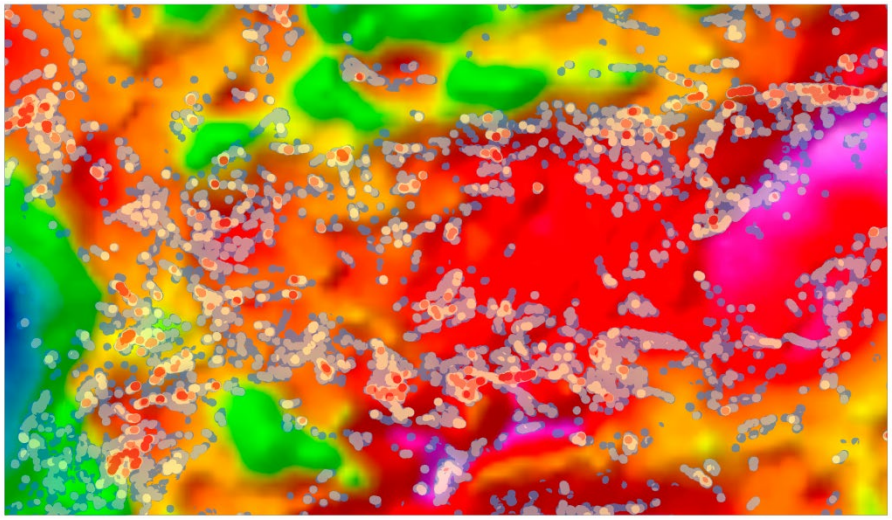
- **increased K/Th**
- **reduced magnetization**
- **electrical conductor in contact**

Insert 12.
Southern Finland, Svecofennian volcanic and schist belts prospective for orogenic gold, VMS and porphyry copper deposits. The geological map is based on the GTK in-house digital bedrock database (Geological Survey of Finland 2010).



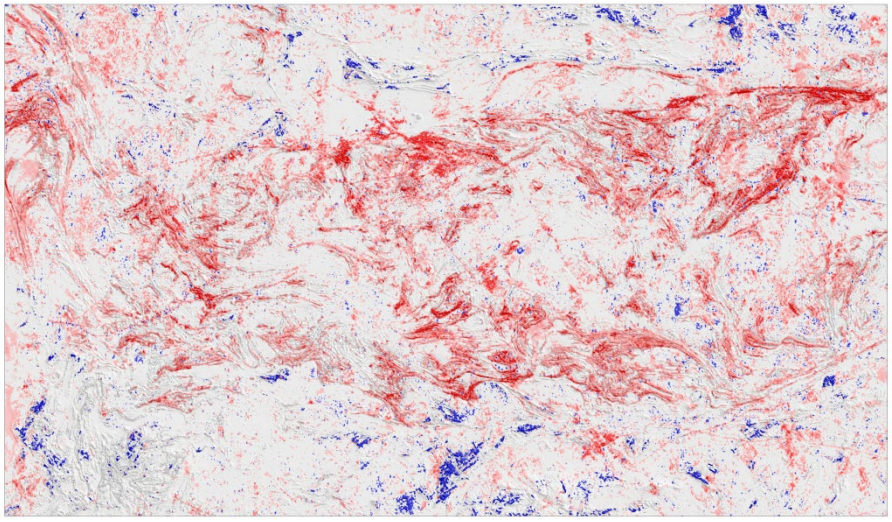
Map area is 170 x 100 km^2.

Bedrock (Digikp 2015)
- light blue = mica gneiss
- pink = granitegneiss
- green = volcanic rocks



Detailed magnetic anomalies are due to pyrrhotite in mica gneiss.
The positive regional gravity anomaly (in red) implies a high metamorphic degree of the migmatitic basin.

High amplitude magnetic anomalies outline the gravity high, and refer to more intense growth of monoclinic pyrrhotite along the margins of the basin, or thickening of magnetic rock units by tectonic processes.



Electrical conductivity aligns with magnetic anomalies of mica gneiss. Volcanic rocks are non-conductive.

Classification of electromagnetic real-component.
- red = conductivity
- blue = magnetite effect

VMS deposits

These occur in volcanic, volcaniclastic and sedimentary rocks and are typically lenticular in shape, and broadly stratiform. They form on and immediately below the seafloor, where discharging high temperature hydrothermal fluids are cooled through mixing with seawater or porewater in near-seafloor lithologies. This process occurs in association with synchronous volcanism and/or plutonism. The primary horizontal extent of VMS deposits varies from tens of thousands of square metres to giant dimensions of several square kilometres. The form of VMS deposits depends on the original hydrothermal geometry and on different post-deformations such as folding, faulting, and shearing. In areas with minimal deformation, deposits can correspond to sheets, layers, lenses, mounds, pipes, and stockwork forms. In deformed areas, the sulphide bodies can be complexly folded and dismembered. The diverse range of deposit morphologies, sizes and also compositions reflects the nature and duration of hydrothermal activity, the topography of the sea floor, footwall and host-rock lithology, temperature gradients, shearing, folding, and faulting, and the degree of erosional preservation. The VMS deposits are commonly developed in extensional tectonic environments, including both oceanic spreading zones and arc terranes. The age range is from the Archaean to modern actively forming deposits. (Galley et al. 2007)

The marked contrasts between the physical properties of minerals associated with VMS mineralization and their host rocks make VMS deposits ideally suited to geophysical exploration (Gibson et al. 2007, Gunn & Dentith 1997). Because all ore minerals in VMS mineralization have high density values, ground gravity surveys have been successful in several cases for first detecting and then delineating the shape and size of unexposed sulphide mineralization. Gravity surveys generally accompany other geophysical (magnetic, electrical, or electromagnetic) and geochemical surveys. They also help to delineate structural alignments or faults and identify structures that potentially provide structural control on the localization of sulphide-bearing ore bodies.

The electromagnetic method has been in a key role in VMS discoveries for decades. Electromagnetic techniques can directly detect conductive base metal deposits. Significant contrasts in conductivity values commonly occur between the ore bodies and their resistive host rocks. Both airborne and ground electromagnetic techniques are effective in detecting massive sulphide mineralization, but only if the sulphide grains in the deposit are electrically connected. When there is a lack of electrical connection, induced polarization can be successfully employed to detect the disseminated sulphides. High-resolution magnetic data can be an excellent tool in identifying the broad geological framework of an area and often show contrasting patterns that reflect differences in lithological compositions, crustal structures, and the type and degree of alteration. There is evidence that sufficiently massive sulphide ores might also be detectable as reflectors revealed in large-scale reflection seismics due to their high acoustic impedance, although the majority of reflectors are due to lithological contacts. Thus, seismic profiles may yet prove useful in direct exploration.

Volcanogenic massive sulphides were the original reason for the development of airborne electromagnetic exploration in Finland. Highly conductive sulphides in massive lenses and combined with base metals (copper, lead, and zinc) may be detectable at great depths with airborne EM. In Finland, the known sulphide deposits are related to steeply dipping or nearly vertical structures, close to the surface. GTK decided to develop its own frequency-domain electromagnetic system with the idea of conducting similar surveys systematically throughout the whole country. The history of this development work is reviewed by Peltoniemi (2005). VMS deposits in Finland have been the most important source for zinc and the second most important source for copper, after the Outokumpu-type deposits. These two deposit types have produced over 90% of the total cumulative production of zinc and copper in Finland (Rasilainen et al. 2014).

In Sweden, the Skellefte mining district includes over 85 VMS deposits that contain the commodities Zn, Cu, Au, Ag, and Pb, and whose geophysical characteristics have been thoroughly investigated.

The deposits are generally characterized by higher magnetic susceptibility, density, chargeability and conductivity than many other rocks (Tavakoli 2012, Carranza & Sadeghi 2010). The VMS deposits are mainly hosted within a volcanic sequence consisting of felsic to intermediate juvenile volcaniclastic rocks, lavas and subvolcanic intrusions. To create a 3D geological model extending to a depth of 10 km, Tavakoli (2012) utilized known geology, petrophysics, seismic reflection data, magnetotelluric (MT) and gravity and magnetic data. Seismic interpretations supported potential field methods for investigating the structure of the key geological contacts and lithological units. Shallow and deeper 3D resistivity and IP investigations (down to ~2.2 km depth) were used for locating previously unknown VMS deposits.

Geophysical key factors for VMS systems

Gravity signature
In general, the VMS-related minerals and ores have high density contrasts with their host rocks. The most common sulphide mineral in VMS deposits is pyrite, which is often associated with other sulphides such as pyrrhotite, chalcopyrite, sphalerite, and galena. Other possible non-sulphide minerals associated in VMS deposits include magnetite, hematite and barite, with densities comparable with most sulphides, and graphite with a typically much lower density (~2.5 g/cm^3).

Magnetic signature
Sulphides with high values of magnetic susceptibility (monoclinic pyrrhotite) are associated with VMS ore bodies. Additionally, non-sulphide metallic minerals with high susceptibility values, such as magnetite (55 000 × 10^{-6} SI) and hematite (40 000 × 10^{-6} SI), may also be common in some massive sulphide deposits and contribute to the strong positive magnetic anomalies. The susceptibility of pyrrhotite is approximately one-tenth of the susceptibility of magnetite. Both of these minerals have high induced magnetization, but pyrrhotite may frequently also have significant remanent magnetization. Magnetite in VMS deposits typically occurs in the core of the stockwork and central basal part of the overlying sulphide lens. Furthermore, magnetite and hematite are common minerals in iron-formation deposits that can be temporally and spatially associated with VMS deposits. Other common sulphide minerals in VMS deposits, such as chalcopyrite, sphalerite and galena, have lower values of magnetic susceptibility that are similar to those found for their sedimentary and volcanic host rocks and thus do not contribute to any magnetic anomaly associated with the VMS ore body. Sphalerite, the most commonly mined Zn-bearing mineral, is not magnetic, is very resistive, and has a relatively low specific gravity.

Electrical signature
Electrical and electromagnetic methods are highly effective in VMS exploration, and various EM techniques are currently used in surveying for VMS deposits. IP methods are also widely used: both massive and disseminated sulphide ores commonly have a high chargeability. Most sulphide minerals, with the exception of sphalerite, are good to excellent conductors, and thus in theory would be easily distinguished from the host rocks by EM methods. Compared to igneous and metamorphic rocks with typical conductivities of <1 mS/m and sedimentary rocks with conductivities from 1 to 500 mS/m, the contrast between VMS deposits and their host rock may be significant (Morgan 2012). Some types of VMS deposits are typically associated with reducing sediments. Noneconomic pyrite-rich or pyrrhotite-rich deposits are not distinguishable from potentially economic deposits, so conductivity and other electromagnetic techniques are not fully definitive exploration tools in VMS exploration.

Graphite has conductivity values similar to sulphide minerals. Anoxic sedimentary rocks that contain graphite or sulphide (metamorphosed black shales in Finland) are also highly conductive, and distinguishing them from massive sulphide deposits may be demanding. The bulk conductivity of deposits may vary

greatly depending on many factors (e.g. deposit geometry, connectivity of electrical conductors – partly dependant on ductility of the material, metamorphic history and tectonic events), so that unlike density, for instance, the conductivity of the ore is not directly proportional to relative mineral concentrations. Under some conditions, massive ores that should be conductive may become resistive and vice versa, some deposits with low sulphide content can be quite conductive. Cu-bearing VMS ores are likely to be more conductive than sphalerite-rich Zn ores. For non-conductive Zn-rich sphalerite deposits in general, IP has been the most successful exploration technique, although EM might perform better, as other sulphides may actually still produce an anomaly. The water content greatly influences the conductivity of a unit. Saturated overburden may produce conductivity values that effectively mask the EM of the VMS mineralization (Thomas et al. 2000).

Radiometric signature

Although no direct indication of VMS ore can be predicted in the natural gamma-ray radiation elements potassium (K), thorium (Th) and uranium (U), some evidence of hydrothermal alteration related to mineralization process (VMS or any other) may be present in the case of shallow deposits (the gamma-ray radiation emits from the upper 0.5 to 1 m of the surface). The processes related to hydrothermal alteration can result in changes in the respective ratios of radiometric elements; K is most often affected by the processes, whereas Th is less often affected and U only rarely. In the case of no weathering or very active mineralizing fluid (causing K depletion), the amount of K is usually increased in the processes (Dickson and Scott 1997). Thus, a ratio of K/Th (or Th/K) could be used in exploration to detect the alteration halos related to mineralization. The origin of such anomalies can be ambiguous and needs to be cross-referenced with topographic and lithological data.

Seismic techniques

Velocities of the most common sulphide minerals are quite variable and range from 8.04 km/s (kilometres per second) for pyrite to 4.68 km/s for pyrrhotite. In comparison, the measured densities are 5.02 g/cm^3 for pyrite to 4.63 g/cm^3 for pyrrhotite. Ore minerals associated with pyrite-dominated ores increase in velocity with increasing density, whereas sphalerite-, chalcopyrite-, and pyrrhotite-dominated ores typically have velocity values that decrease with increasing density. Host rocks have a much narrower and lower range of density values and have a wide range of velocities. Seismic reflectivity is controlled by several factors, but one dominant factor is the difference in impedance between lithologies (Salisbury et al. 1996). Impedance is defined as the product of density and compressional wave velocity in a given material. Measurements of the specific gravities and velocities of common silicate rocks and ore minerals indicate that ore minerals have significantly higher density values and a broad range of velocities, and therefore tend to have higher impedances than their host rocks. The difference in the impedance value between the ore body and its host rock can be significant enough to result in high amplitude reflections and identification of the ore body.

In Finland, zinc deposits of possibly VMS category occur in three main geological settings: in Palaeoproterozoic Svecofennian arcs, in Palaeoproterozoic rifts and in Archaean greenstone belts. Vihanti, Pyhäsalmi and Rauhala belong to the group of Svecofennian VMS deposits in central Finland and resemble the Skellefte ore field in northern Sweden. Another group of this kind is located in southwestern Finland, where Orijärvi, Aijala and Metsämonttu have many similarities with the Bergslagen region in Sweden. If VMS deposits are classified into mafic, bimodal-mafic and felsic types (Rasilainen et al. 2014), Pyhäsalmi represents the felsic type. VMS deposits do not necessarily produce any significant airborne geophysical expression, as can be seen, for example, for the Rauhala deposit in Figure 7.

Hammaslahti is an example of rift-related zinc deposits in southeastern Finland. This sediment-hosted massive sulphide Cu-Zn-Au deposit has

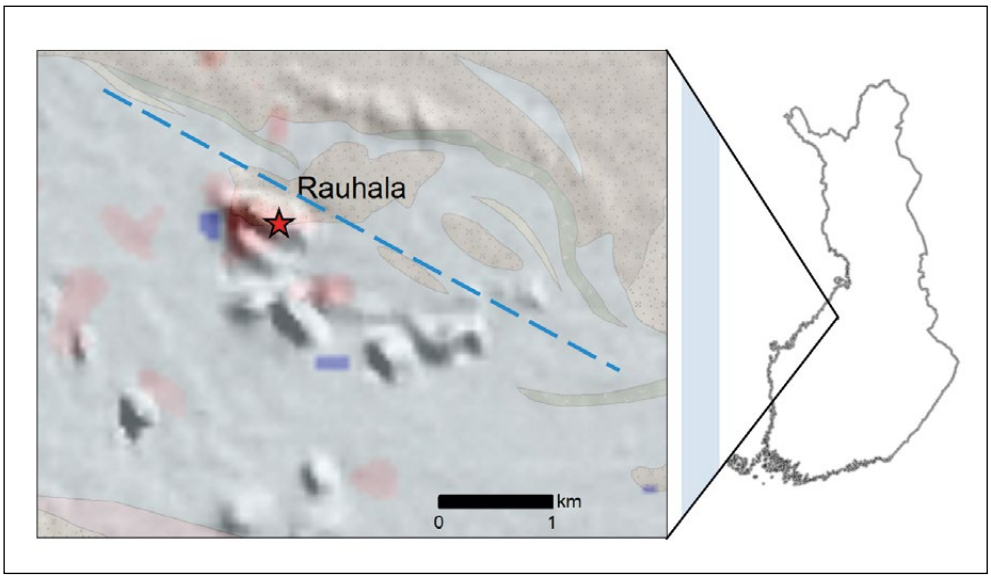


Fig. 7. The Rauhala VMS deposit is situated along a regional NW–SE-oriented fault (blue dashed line) and has weak magnetic and conductivity signatures. Magnetic derivative with a background geological map, based on the GTK in-house digital bedrock database (Geological Survey of Finland 2010) and the electromagnetic ratio as an overlay (conductivity anomalies in red).

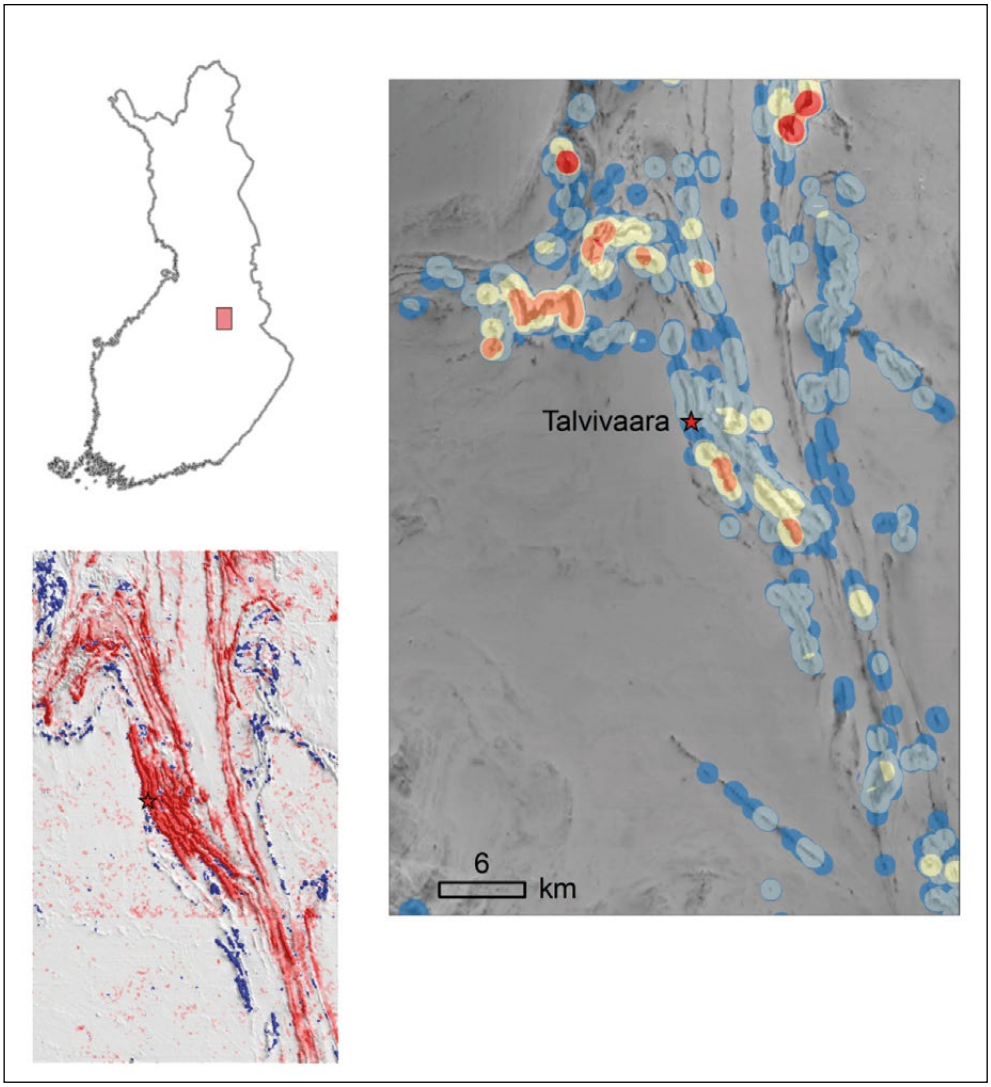


Fig. 8. The black schist-hosted Talvivaara Ni-Zn-Cu-Co sulphide deposit in eastern Finland.
Left: Conductivity anomalies (in red) are enhanced on the basis of AEM classification.
Right: Magnetic anomaly classification (see colour scale in Insert 5).

been regarded as either of the SEDEX or mafic VMS style. Two-phase pyrrhotite, a hexagonal form together with the monoclinic type, has been reported by Airo & Karell (2001).

The Häme belt in southern Finland is considered to be highly prospective for VMS deposits. Leväniemi & Karell (2013) describe geophysical indications of possible VMS targets in the Häme belt and give an appraisal of how regional datasets work in VMS exploration. They describe geophysical characteristics for several deposits and present new petrophysical data measured from drill cores. *Insert 12* presents a regional overview of the magnetic, gravity and electromagnetic data from the Häme-Pirkkala area. The folded, small-scale magnetic anomalies in migmatitic rocks are due to pyrrhotite, probably of metamorphic origin. Electrical conductivity anomalies coincide with magnetic anomalies. The migmatitic rocks form a basin that is associated with a positive regional gravity anomaly (in red), also implying the high metamorphic degree of the area. High amplitude magnetic anomalies are found surrounding the gravity high, referring to more intense growth of monoclinic pyrrhotite due to tectonic processes along the margins of the basin.

The graphitic shale-hosted Talvivaara Ni-Zn-Cu-Co deposit in eastern Finland is one important resource of copper and zinc. It is hosted by Palaeoproterozoic (2.1–1.90 Ga) carbonaceous metasedimentary rocks of the Kainuu schist belt (Loukola-Ruskeeniemi & Heino 1996, Loukola-Ruskeeniemi 1999). More than 20 occurrences and one operating mine of Talvivaara-type metal-enriched black schists (metamorphosed carbonaceous muds) occur in 2.0 ± 0.1 Ga sequences of metasedimentary

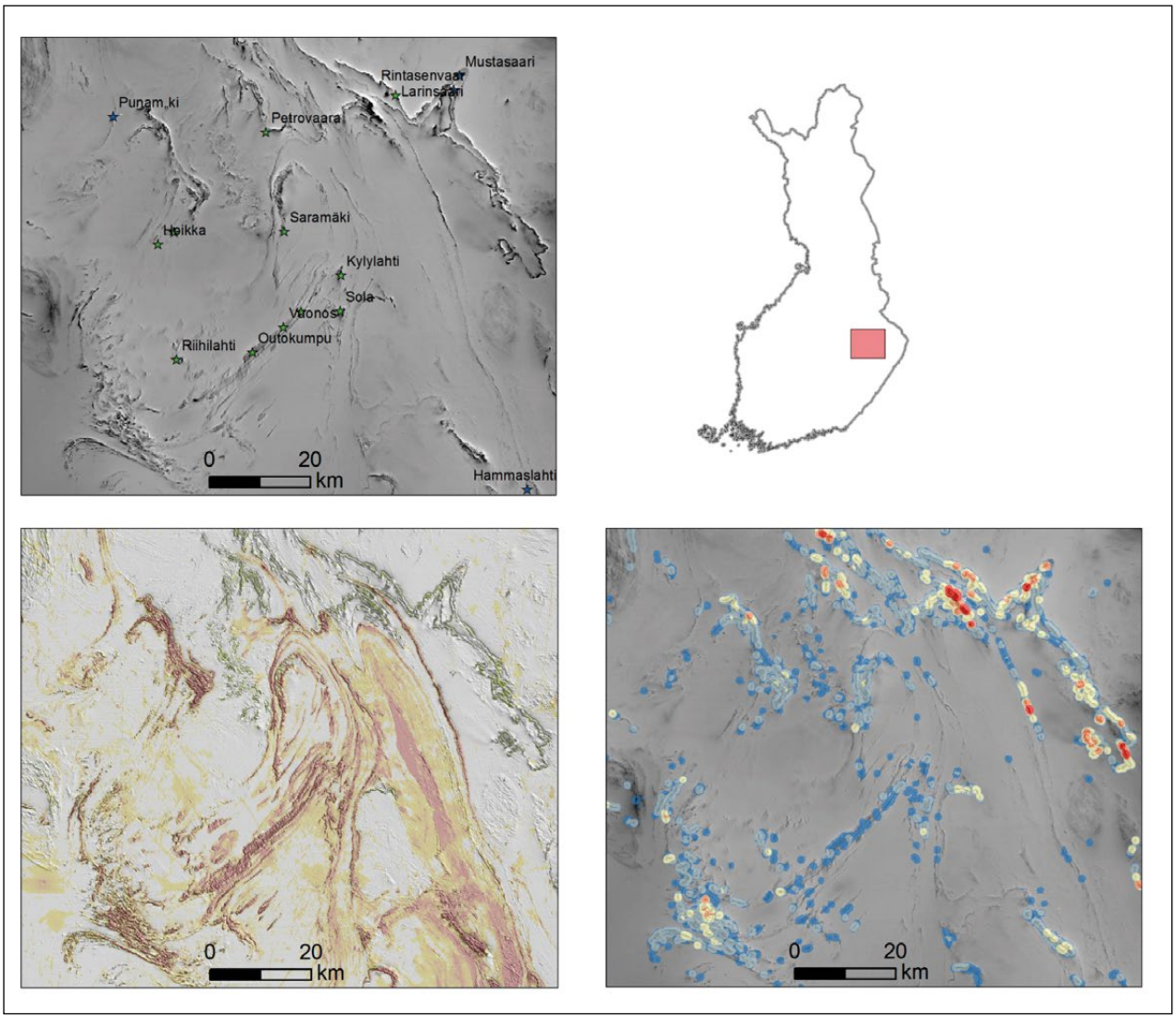


Fig. 9. Outokumpu-type Cu-Zn-Co deposits (green = Cu, blue = Zn). Upper left: Aeromagnetic map (Mineral deposits FODD 2013); lower left: conductivity anomalies (in red), enhanced on the basis of AEM classification; lower right: magnetic anomaly classification (see colour scale in Insert 5).

rocks in the Kainuu and North Karelia schist belts (brief description in Rasilainen et al. 2012). The highest and the most uniform concentrations of base metals in the Talvivaara-type deposits occur in pyrrhotite-dominated parts. Geophysical signatures of Talvivaara include moderate magnetic anomalies due to monoclinic pyrrhotite, high-intensity conductivity anomalies and U radiation revealed by airborne radiometric data (Fig. 8). U-radiation values are typically high along the regional crosscutting faults, referring to enrichment of uranium. Organic materials, clay minerals, Fe^{3+}, Mn and Ti also have a role in the enrichment of U (Airo & Hyvönen 2008).

The Cu-Zn deposit types in Finland where copper, zinc or both occur as main commodities are VMS deposits, porphyry copper deposits and Outokumpu-type Cu-Zn-Co deposits (Fig. 9). All the known Finnish Outokumpu-type deposits occur in a rather restricted area in eastern Finland. Petrophysical properties of the Outokumpu Deep Drill Core have been reported by Airo et al. (2011).

Banded iron formations and IOCG-style FeCu, Au

The magnetic signature of iron deposits depends on whether the mineralization is in the form of magnetite or hematite. The presence of strong remanent magnetization, demagnetization, and the markedly anisotropic nature of the magnetic properties of banded iron formations (BIF) may complicate the interpretation of magnetic surveys (Hagemann et al. 2007).

Banded iron formations
are usually associated with Precambrian (Archaean to earliest Palaeoproterozoic successions) sedimentary sequences, which typically contain shales, dolomites and volcanic mafic rocks. The presence of a large supply of iron in ocean water from hydrothermal sources was one reason for the global accumulation of BIFs in the Precambrian period. Favourable structures for BIF-hosted gold deposits are fold hinge zones or faults, or shear zones intersecting an iron formation, and their alteration style is chlorite-carbonate or amphibole alteration and sulphidation of iron formation. Geophysical tools are used in structure mapping, identification of stratigraphy and faults controlling fluid movement, and finally in direct detection.

Geophysical characteristics of BIF

Magnetic method
- traditionally, the magnetic method is used to map the magnetite rich rocks that host the deposits
- iron oxides may be strongly magnetic (remanent magnetization)
- magnetite destruction associated with magnetite oxidation and deep weathering to hematite and resulting in low magnetic anomaly intensity
- destruction of magnetic anisotropy or magnetic fabrics
- obligatory for structural and stratigraphy mapping

Gravity method
- airborne gravity gradiometry systems, but ambiguity in the density contrast
- density of magnetite and hematite >5 g/cm^3

Radiometric method
- at a local level, the down-hole radiometric method is most useful: lithological information
- airborne radiometric measurement to assist in structural and stratigraphy mapping

DC resistivity, induced polarization, electromagnetic and seismic methods
- mainly as problem-specific solutions; stratigraphic and structural mapping with magnetics
- conductivity of iron formation: min 0.05 – max 3300 mS/m (Morgan 2012)
- frequency domain EM: the ability to differentiate magnetite
- deeper looking: airborne transient electromagnetic method (TEM)

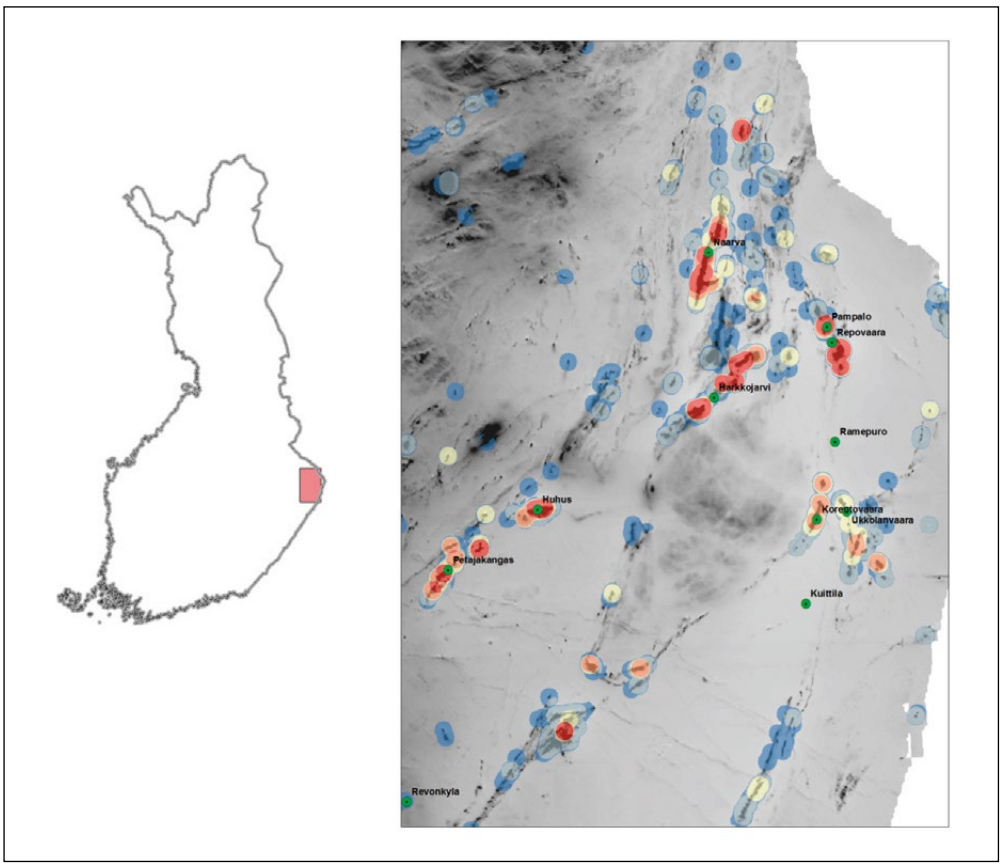


Fig. 10. Magnetic anomaly classification of the Hattu belt. The map area is 50 km wide. Colour categories are explained in Insert 5.

In Finland, the Huhus Fe area as part of the Hattu belt contains banded iron formations (BIF) of Archaean age (Sorjonen-Ward & Luukkonen 2005), where the Fe deposits have been delineated by their geophysical indications. Magnetic anomaly classification (Fig. 10) shows the distribution of the BIFs as high-amplitude anomalies. High-amplitude magnetic anomalies also characterize the Misi area in Figure 11 (F039 by Eilu et al. 2012, Niiranen et al. 2003). In southern Finland, Fe mineralizations of skarn and banded iron formation types occur as part of the Orijärvi Zn-Cu-Pb+Fe zone (Saltikoff et al. 2006). They belong to the same type as the Zn-Cu-Pb and Fe deposits of the Bergslagen province in Central Sweden.

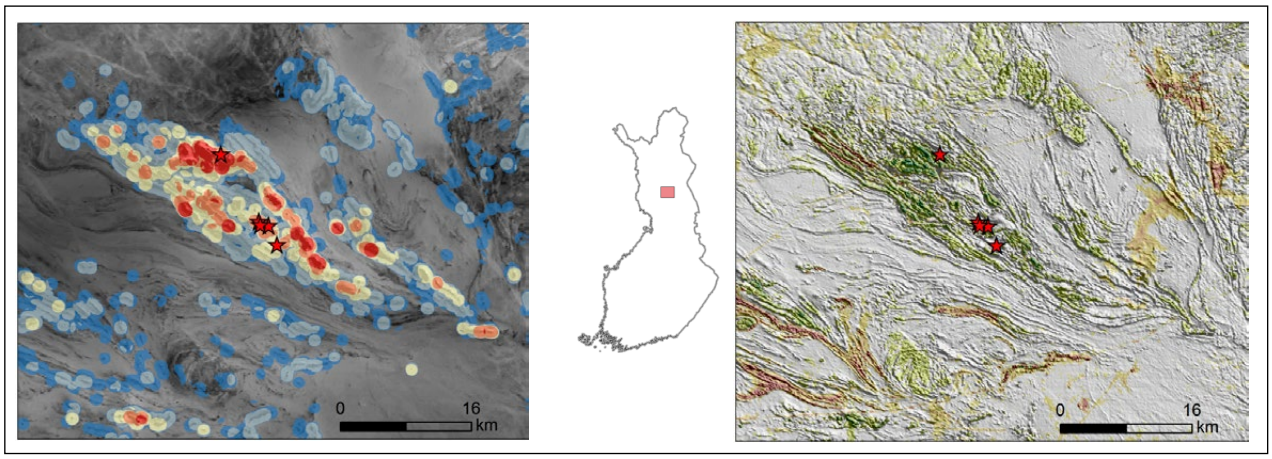


Fig. 11. Misi area: magnetic anomaly classification (left), colour categories are explained in Insert 5; electromagnetic classification (right), red = conductive, green = magnetite.

IOCG deposits
have been successfully explored by magnetic, gravimetric, electrical and radiometric methods. However, the complex structure and diverse materials complicate geophysical interpretation. The IOCG districts are well controlled by structural and/or stratigraphic factors with ore occurrences typically confined to fault bends, shear zones, rock contacts, breccia bodies, or as lithology-controlled replacements, and they are associated with extensive prograde and retrograde alteration (Groves et al. 2010). IOCG-related hydrothermal systems share certain distinguishing features, notably including (1) extensive alkali-rich alteration, (2) voluminous low-Ti magnetite and/or hematite, (3) a distinctive suite of minor elements (REE, Co, Ag, ± U, P), and (4) prominent structural control.

Exploration methods presently utilized include regional geology, detailed geological and alteration studies, airborne and ground geophysics (gravity, magnetic, radiometrics, induced polarization and electromagnetic) and geochemistry (Smith 2002, Barton & Johnson 2004). A Titan-24 array magnetotelluric survey has been successfully used to locate conductive bodies at greater depth. However, even in ideal cases, geophysical interpretation can be complicated by the varied and complex origins and fates of Fe oxides, Cu-Fe sulphides and alteration minerals.

Geophysical footprints of iron-oxide Cu-Au (IOCG) deposits

- Fe-rich host rocks; the abundance of iron oxides (magnetite or hematite) produces very strong magnetic anomalies
- Typical ore minerals: magnetite, pyrite, pyrrhotite, Cu sulphide
- A deficiency or irregular presence of sulphides, but generally highly conductive
- Widely developed hydrothermal alteration (commonly U and Th)
- Regional albititisation; potassic and sericitic alteration may be detectable with a gamma-ray spectrometry survey;
- Local alteration: Fe-, Na-Ca- and K-metasomatism
- Crosscuts the primary bedding and is associated with shear zones; are associated with coincident magnetic and gravity highs
- In Finland, close to the Archaean/Proterozoic boundary (±100 km).

after Barton & Johnson (2004)

In Finland, well-known deposits include Hannukainen and Rautuvaara in western Lapland, and Vähäjoki in southwestern Lapland (Billström et al. 2010). Magnetic anomaly classification in *Insert 5* indicates many of the known IOCG prospects that are located around the granitoid massif in central Lapland. In northern Sweden, apatite-Fe ores, porphyry-Cu and Fe oxide Cu-Au deposits have been proposed to be related (Sandrin et al. 2007). The famous Kirunavaara and Malmberget mines belong to the apatite-Fe subclass, and have been producing around 31 Mt of ore per year during the last 100 years.

Petrophysical properties of rock samples representing various mineral deposit types, including magnetite-type IOCG mineralization, were investigated for comparison of their associated airborne geophysical signatures (Airo & Säävuori 2013). A dominant remanent magnetization component was verified for magnetite-type IOCG test samples as having high Q-ratio values. This knowledge was used in the method for magnetic anomaly detection by classifying magnetic anomalies (Airo et al. 2014).

Porphyry Cu-Au

Porphyry deposits are igneous in nature, and may have a cylindrical or torus shape, thus in an ideal case producing a near-circular geophysical response. The porphyry deposits are the largest source of copper and molybdenum in the world and a significant storage of gold and silver. The porphyric systems have been formed from the Archaean to the Quaternary in age. Large economic deposits of Cu and Mo are associated with these intrusives in South America, Asia and North America, and the geophysical properties of this type are well documented. In a general sense, magnetic field data delineate the geological structure relatively well, and are best suited for this purpose. While the main economic mineralization may only be moderately conductive, the pyrite halo and secondary mineralization may be very conductive, and could be an excellent EM target. The large size of the intrusives could make them excellent targets for regional mapping. Radiometric and hyperspectral surveys can be useful in arid climates to aid in identifying the lithology and search for characteristic alteration minerals. Interpretation may require a solid understanding of the expected alteration patterns rather than the actual ore mineralization distribution.

Porphyry deposits
are generally related to shallow located intrusive complexes and underlying plutons and batholiths, where volcanic rocks typically have dioritic to granitic compositions. Porphyry systems are surrounded by different rock types such as igneous, sedimentary and metamorphic rocks. The deposit grade can be raised by the presence of a particular lithology of the hosted rocks. For instance, the concentration of high-grade ore can be formed in carbonate successions (especially like marble) or other fine-grained and low-permeable rocks that may seal a porphyry deposit all around. Lithological clusters, which are rich in ferrous iron, can also assist in high-grade porphyry mineral accumulation. Porphyry districts are associated with the subduction of submarine ridges and seamount chains, and oceanic plateaus beneath continental arcs. (Sillitoe 2010)

Summary of general geophysical properties:

- to some extent magnetic: contrast positive or negative, depending on host rock magnetization;
- potassic intrusions, hydrothermal (potassic) alteration zones, are in an ideal case detectable by the radiometric, and even the aeroradiometric method;
- disseminated sulphide mineralization: IP method;
- circular shape (if no tectonic deformation) possible to distinguish by pattern recognition.
- Oasis montaj offers software system (CET porphyry analysis, 2012) to analyse the shape of gridded geophysical anomalies to detect near-circular, symmetrical features of a given range.

These intrusion-related gold-copper occurrences are associated with syntectonic granitoids in and close to the Archaean-Proterozoic margin, for example Kopsa in central Finland. A suspected occurrence is Kedonojankulma in the Häme belt (Mertanen & Karell, p. 89, Kuosmanen et al., p. 117). Neither of these possesses any clear or detectable signature in airborne geophysics. The open pit mine of Aitik (Gällivare, Sweden) is a major Cu-Au producer and the only sizable porphyry-Cu deposit presently mined in Sweden.

Insert 13 shows an example of a circular magnetic anomaly ring (visual inspection) surrounded by magnetic and radiometric haloes (potassium and uranium radiation data). This type of combination would be a typical geophysical signature for porphyry systems; so far, no deposit has been identified at this site.

Geophysical key factors for Cu-Au porphyry deposits

Magnetics
Many of the intrusive complexes driving porphyry mineralization will to some extent be magnetic and will contrast either positively with volcanic and sedimentary country rocks, or negatively with highly magnetic volcanic country rocks. Hydrothermal alteration in porphyry systems can provide distinct signatures, for instance, magnetite in K silicate alteration zones in the core of the system, intense magnetite replacement in peripheral skarns, and magnetite alteration or destruction in volcanic rocks adjacent to intrusions.

Radiometrics
Radiometric data, usually collected in conjunction with magnetic data during airborne surveys, are an excellent aid to geological mapping. In porphyry settings, a radiometric survey can quickly identify both potassic intrusions and potassic alteration zones if they are at the surface. Generally, however, in areas of good outcrop, these indicators have already been detected by geological work, so surface radiometric methods have rarely had a major role in porphyry exploration.

Gravity
The porphyry model can be used to predict that there may be significant, sharp density contrasts between intrusive and country rocks, but that recognizable contrasts related directly to alteration and mineralization are much less likely because these features usually have a disseminated character and diffusive boundaries.

Induced polarization (IP)
IP is particularly suited to detecting large bodies of disseminated sulphide mineralization and, if used extensively, to producing a three-dimensional sulphide distribution map of a prospect area. It is an excellent method for detecting subsurface phyllic zones within porphyry systems, because these zones usually have the highest sulphide content, mainly pyrite.

Electromagnetic (EM) methods
EM methods have not been extensively used in porphyry exploration. Conductivity contrasts tend to be moderate and diffusive in the porphyry environment, and resistivity has always been an accessory measurement during IP surveys for porphyry exploration, but it has not been a significant discovery tool. A recent development is the co-acquisition, during distributed acquisition IP surveys, of DC resistivity and magnetotelluric (MT) resistivity data. Combined TDEM and magnetic surveys and inversion of electromagnetic data have been used to locate conductive bodies >400 m below the surface. 3D inversion of time-domain airborne EM data, combined to ZTEM airborne audio-frequency magnetics, has recovered conductors coincident with alteration (Pare et al. 2012).

Seismics
The use of seismic methods is rare in porphyry exploration. It is possible that the use of seismic methods will increase in covered areas where strata generally dip less than 45°, with the aim of determining the cover thickness, volcanic architecture beneath the cover and overall structural architecture.

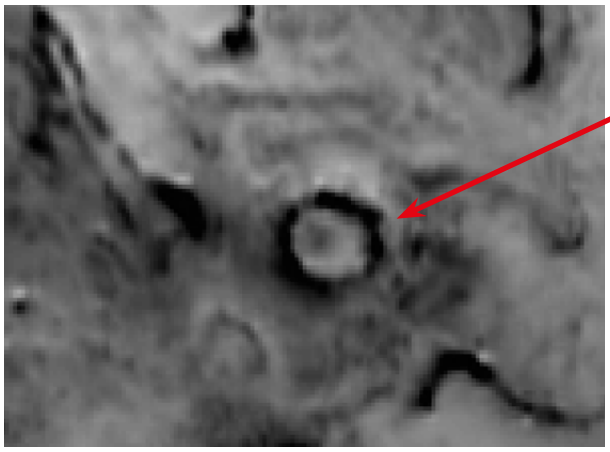
Spectral scanning methods
Airborne multi-spectral scanning methods have also not had a major role in porphyry exploration, although this technique can discriminate complex phyllosilicate alteration assemblages efficiently, something which can be very important in porphyry lithocap settings. The more standard approach in these settings is to use hand-held devices on rock samples and drill cores. A significant development in this direction is the HyLogger™, a semi-automated core-logging device that combines rapid hyperspectral mapping of mineralogy and very high resolution imaging of cores (Huntington et al. 2006). The device can identify phyllosilicates, amphiboles, carbonates, sulphates and iron oxides, and with the recent addition of scanning in the thermal infra-red spectral range will recognize quartz, feldspars, garnets, olivines and pyroxenes. The ability to rapidly (~100 core trays per day) and objectively collect such data and

then interpret these data in terms of alteration zones utilizing the porphyry model would be a significant advance for exploration targeting in an advanced porphyry exploration project, and may be of particular benefit for targeting mineralized zones within or beneath lithocaps.

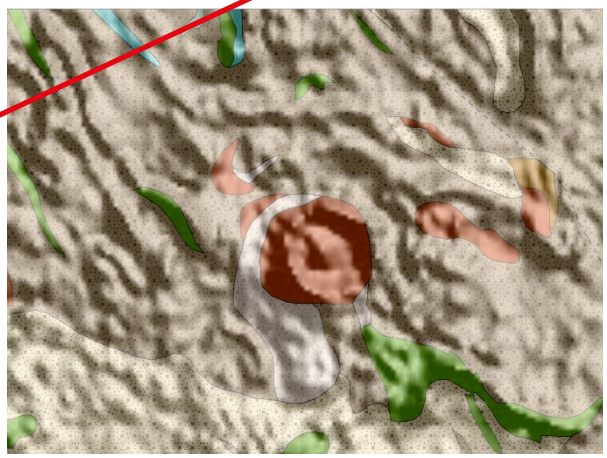
after Holliday & Cooke (2007)

Insert 13.
Example of a circular magnetic anomaly surrounded by magnetic and radiometric haloes (potassium and uranium radiation data). This type of combination would be a typical geophysical signature for porphyry systems or an impact crater.

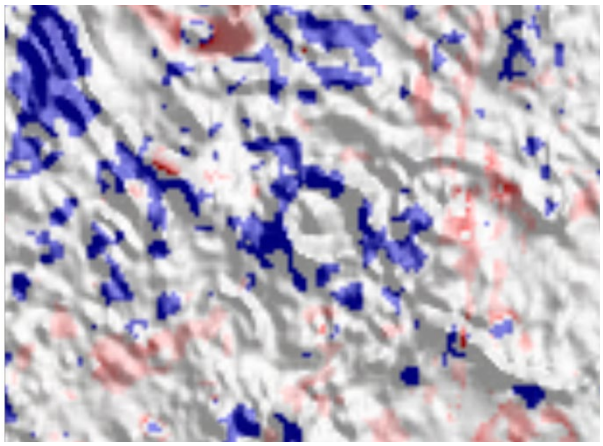
Magnetic field derivative enhances shallow structural features. Radiometric data sets were improved by masking out the low – value noise that may be due to wet areas. Electromagnetic ratio map (the ratio of the real to the imaginary component) reveals magnetite bearing units in blue. The geological map is based on the GTK in-house digital bedrock database (Geological Survey of Finland 2010).



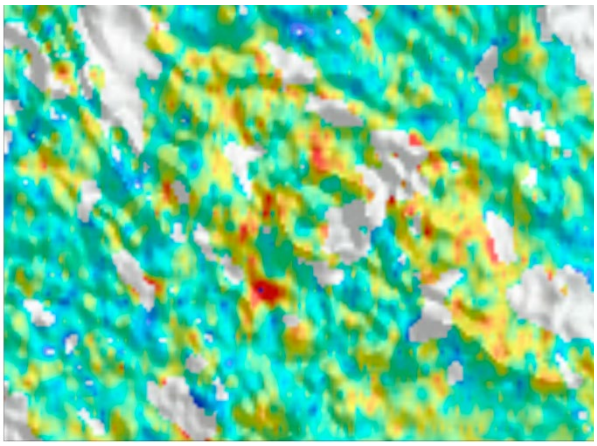
Magnetic field (total intensity). Positive anomalies are dark. The map area is 8 km wide.



Bedrock (Digikp2015) + Magnetic field derivative. Brown = gabbro, green = volcanic rock.



Electromagnetic ratio Re/Im + Magnetic field derivative. The magnetic ring is caused by magnetite.



K (potassium) + Magnetic field derivative. High K radiation (in red) around the magnetic ring.

High-tech minerals and uranium

The discussion here includes so-called high-tech metals (Nb, Ta, In, REE), rare-element pegmatites (Li) and uranium (U). Rare earth metals are characteristically associated with carbonatitic and alkaline intrusions, pegmatites and intrusive dykes. The discovery of intrusion-related rare earth metals has been based on a variety of exploration techniques and occasionally by chance. Geophysical methods are successful only if there is a sufficiently large contrast in the rock properties of the investigated geological units. For example, indium (In) may occur with base metal sulphides so that conductivity might be observed. Intrusive carbonatites typically show concentric zoning of carbonate and alkalic rocks. Variable concentrations of magnetite in these zones produce strong magnetic anomalies dominated by remanence, such as Nb and REE-bearing Sokli carbonatite in northern Finland. Uranium prospects in northern Finland are discussed by Lauri & Turunen *(p. 107)*.

Geophysical methods for REE minerals

Gravity method
Many of the REE minerals have a higher density in comparison with country rocks. Ground gravity data yield sufficiently high resolution, but these surveys can only be focused on small areas. Modern airborne gravity methods may be promisingly effective for the detection of intrusions hosting rare earth metals. Density values for the alkaline and carbonatitic rocks may be in the range of 2.8–3.1 g/cm^3, compared to country rock vales of 2.7–2.75 g/cm^3. Aligned with the gravity anomaly, the magnetic gradient anomaly and the radiometric expression may help in discovering promising targets for more detailed evaluation.

Magnetic method
REE minerals themselves are commonly weakly magnetic, but their host rocks may produce significant magnetic anomalies. Carbonatitic-alkalic complexes potential for rare earths may produce circular magnetic anomalies with amplitudes attaining several thousands of nT and which coincide with a radiometric response. Recently automated methods in locating circular magnetic anomalies have become popular. The carbonatite cores may coincide with magnetic lows, whereas the surrounding ring-like anomaly may be associated with magnetite-bearing carbonatite or a ring of alkali rocks. In Finland, the Sokli and Iivaara carbonatite complexes produce strong magnetic anomalies.

Radiometric method
The airborne radiometric method has proved to be efficient in detecting equivalent thorium or uranium anomalies, even in glaciated terrains. For example, the radiometric method has been successful in outlining different parts of the intrusion of Sokli carbonatite (e.g., Airo et al. 2014). The equivalent thorium signature also outlines the glacial dispersal train.

Thomas et al. (2011) reviewed the rock properties of 28 minerals that may contain rare earth elements, and showed high densities of almost all of these minerals, with a general range of 3.26–5.90 g/cm^3. Many of these minerals are radioactive, and practically all are non-magnetic. The direct detection of these minerals, however, depends on their concentration and the size of the deposit. Therefore, their detection is generally based on the detection of promising host rocks.

Kihlman et al. (2014) presented a list of 14 metals and minerals that are considered as critical by the EU; these include antimony, beryllium, cobalt, fluorite, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals (PGM), rare earth elements (REE), tantalum and tungsten. They reviewed the mine production (2013) of critical commodities (including silver) and the most important known platinum group element deposits in Finland, and predicted the mineral potential.

Rare element pegmatites can only be described as geophysical non-responders. They are non-magnetic, they contain insufficient metallic minerals to be conductive and do not have a sufficient den-

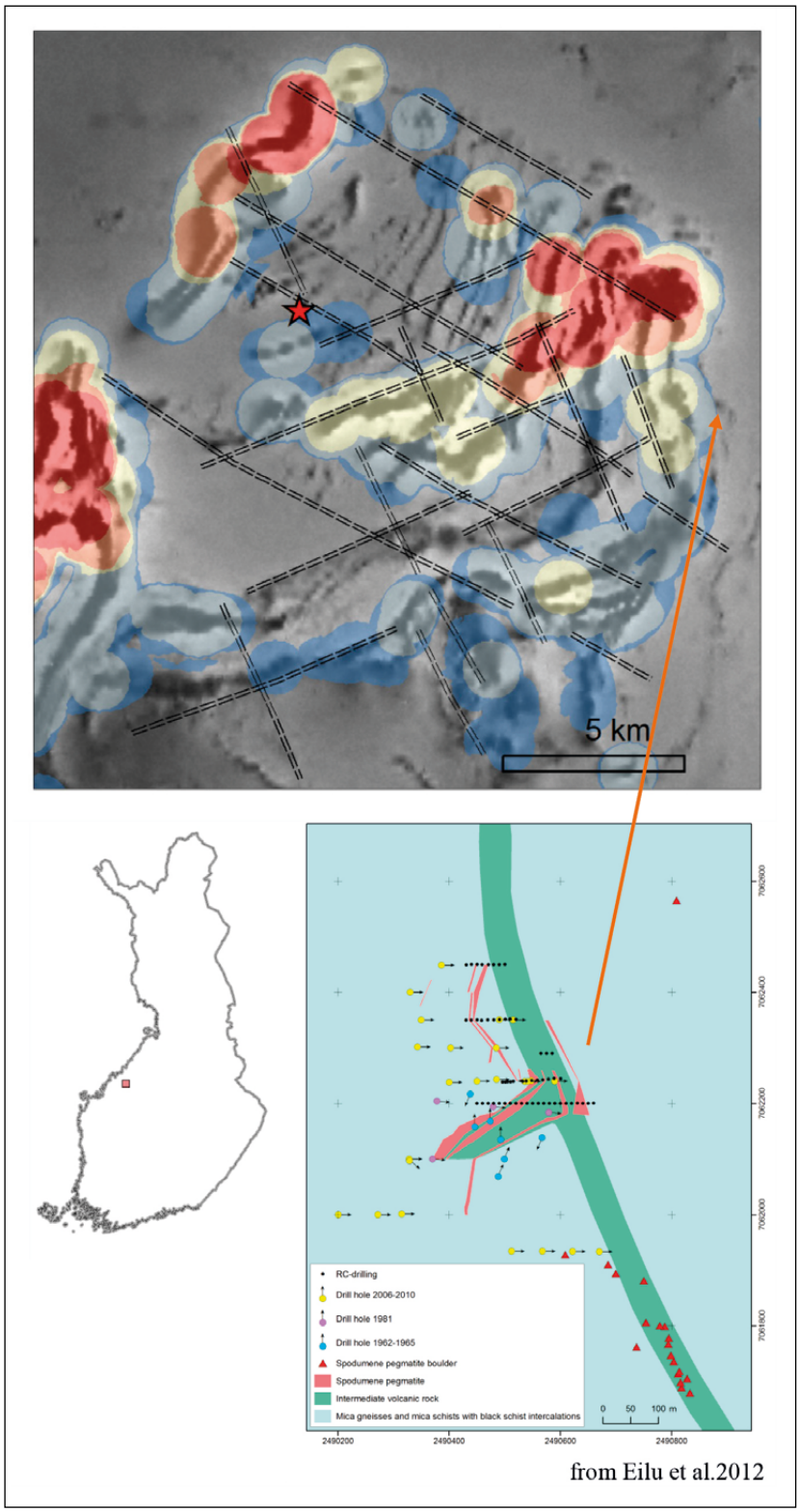


Fig. 12. The LCT (Li, Cs, Ta) pegmatites at Kaustinen (metallogenic zone F024, Eilu et al. 2012) include several occurrences from Emmes (red star) in the west to Länttä in the east. The pegmatitic dykes are 200–400 m long and 10–25 m wide and show no geophysical expression. A regional structural overview of fracture network indicates that all the occurrences are located along fracture zones of two certain directions. These directions also are related to the weakness structures of volcanic rocks in the area and their brittle nature gives the idea that they were formed after the peak regional metamorphism. In particular, in the Syväjärvi spodumene pegmatite area (local geology to the right, from Eilu et al. 2012), the geometry of the pegmatitic dykes appears to be controlled by the structural details of the intermediate volcanic rock along the strike of bedding and along the crosscutting axial weakness zone of regional folding.

sity/mass to be differentiated from their host rock by gravity methods. Structural interpretation of high-resolution geophysical data might, however, be a non-direct way of locating favourable sites for rare element pegmatites. The following general structural characteristics are from Galeschuk & Vanstone (2007):

- dyke-like geometries,
- propagation in horizontal and vertical directions,
- association with deep-seated structures and fractures,
- host rock competency and metamorphic grade may have some importance.

In the case of lithium occurrences at Kaustinen, western Finland, structurally favourable locations for pegmatitic dykes were investigated by using high-resolution aeromagnetic data (Fig. 12).

CONCLUDING REMARKS

The direct use of geophysical surveys in mineral exploration aims to locate and identify potential targets having anomalous physical properties. Further uses are the delineating of the larger-scale structures in the deposit they may be related to, or the investigation of finer scale detail within the deposit. However, direct targeting of new shallow-level mineral deposits is becoming increasingly rare. A key element for exploration is to understand and detect different types of mineral systems, and their favourable geological settings and controls at regional to local scales (Oldenburg & Pratt 2007). In Finland, as early as in the 1980s, Ketola (1982) summarized that since exploration is becoming more and more difficult, geological knowledge must be increasingly supplemented by the application of geophysics to indirect exploration. If ores are to be found, the most effective use must be made of the simultaneous application of geology, geophysics, geochemistry and drilling.

An understanding of the physical properties of rocks and minerals provides a link between geophysical interpretation and geology. The importance of reliable physical property information is enhanced as 3D interpretation, modelling and inversion of geophysical data are becoming common practice. Available geological knowledge must be translated into physical property constraints to derive models that are consistent with measured geophysical responses and the observed geology (Williams 2009). The non-uniqueness of geophysical modelling solutions is both a mathematical problem and one related to the multiplicity of sources that can cause geophysical anomalies.

Looking back

In the last decade, significant advances have been made in proven geophysical methods and in techniques to interpret and visualize geophysical data. The data models have been visually integrated, but not necessarily constrained. Such advances reach their full impact through appropriate consideration of the physical properties of rocks in relation to the key manifestations of the different deposit types and the key features of their host environments.

Exploration 07, Paine 2007:

Inversion of all types of geophysical data has doubled its importance and use in the past decade. There has been a general improvement in the quality, density and variety of geophysical data collected. Airborne surveys now usually use GPS navigation and improved positional accuracy. Improvements in data acquisition devices also mean that the data measurements are more accurate and more closely spaced. Developments of sensor types such as gravity gradiometer, squid-based B-field sensors for collecting magnetic and EM data have been reported. Increased data density has been accompanied by improved processing techniques for improving data quality. Processor speed, available memory and storage space have all increased significantly in the last ten years.

Exploration 07, Oldenburg & Pratt 2007:

Developments in instrumentation, data collection, computer performance, and visualization have been catalysts for significant advances in modelling and inversion of geophysical data. Forward modelling has progressed from simple 3D models to whole earth models using voxels and discrete surfaces. Potential field, IP and electromagnetic inversion methods have become an essential part of most mineral exploration programs. The last decade has produced

significant research advances in 3D modelling and inversion for gravity, magnetic, DC resistivity, induced polarization, audio magnetotelluric, frequency-domain EM and time domain EM methods.

Challenges

- ***Simultaneous analysis of multiple datasets,*** which contain information about different physical properties. To maximize the efficiency of exploration programmes, it is essential that multidisciplinary methods include all geological, geochemical and geophysical data and knowledge in integrated models. The trend towards multi-sensor systems using multiple low-cost sensors and receivers has been ongoing. Increasing computer power will make detailed 3D imaging of most surveys possible, as well as joint and cooperative inversions. The challenge is to use physical properties more quantitatively to link geological and geophysical models.
- ***Joint and cooperative inversions*** will offer a greater opportunity to integrate different types of data into the interpretation procedure. Applications include the inversion of full tensor magnetic and gravity data, cross-gradient total field surveys, DC resistivity and EM data, and many others (Oldenburg & Pratt 2007). The use of optimized geophysical data, e.g. derivative data that have been converted into forms, can facilitate the inversion process. A vast increase in the size of problems that can be handled includes the introduction of practical voxel-based 3D magnetic, gravity and IP inversion programs and the ability to include topography in 2D and 3D inversion, as well as the capacity to include drilling and geological information to constrain the inversion. Progress has also been made in including remanence and demagnetization effects into magnetic inversions (Paine 2007).
- ***Geophysical techniques reaching greater depth*** are gaining interest with the depletion of metallic mineral sources in surface or near-surface settings. Exploration must focus at much greater depths, which requires sophisticated techniques. Whereas potential field geophysical techniques or combined airborne electromagnetic and magnetic surveys have been highly successful to depths of up to 300 m, high-resolution seismic reflection profiling can target much greater depths. The seismic methods have good potential for mineral exploration, and these methods are capable of imaging mineral deposits at various depths (Tertyshnikov 2014). Recent interest in finding deeper sources has led to the development of deeper penetrating electromagnetic systems: high-resolution and deep-penetrating surveys, e.g., ZTEM, Megatem™, magnetotellurics and the Titan array (Boivin 2007).
- ***Geologically realistic outputs:*** Petrophysical data can, if available in sufficient quantity, constitute a basis for statistically characterizing and constraining the property distribution in the sub-surface. Although textbook physical property values are commonly used, ancient rocks have complex histories and standard values may not be representative. The ability to simultaneously model and interpret geophysical, geological, geochemical and geotechnical data will reduce geological uncertainty. The characterization of a mineralized target depends as much on data accuracy and coverage as it does on a good representation of the subsurface. In this sense, inversion approaches that fit the source geometry and properties are constantly improving. After inversion of pure property models, geology can be inferred from the rock properties (Fullagar & Pears 2007, Jessel 2001, McGaughey 2007). Obtaining reliable images of subsurface geological structures is a great support for successful mineral exploration, and there are a number of further developments and improvements in seismic imaging that will allow their advanced applications in the mining industry.

Looking forward

The enormous quantity of multiple geophysical sets that are nowadays available may require automated methods of analysing and evaluating the data. Sophisticated inversion techniques are needed, incorporating adaptive learning procedures to determine complex 3D geometries of source bodies. Greater volumes of petrophysical data will allow more complete spatial characterization of rock properties, thereby expanding the role of geostatistical techniques in property modelling. Mappable criteria to be applied in mineral system research are provided by wider knowledge of the petrophysical properties of mineralized or barren source rocks responsible for geophysical responses.

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