GEOLOGICAL SURVEY OF FINLAND
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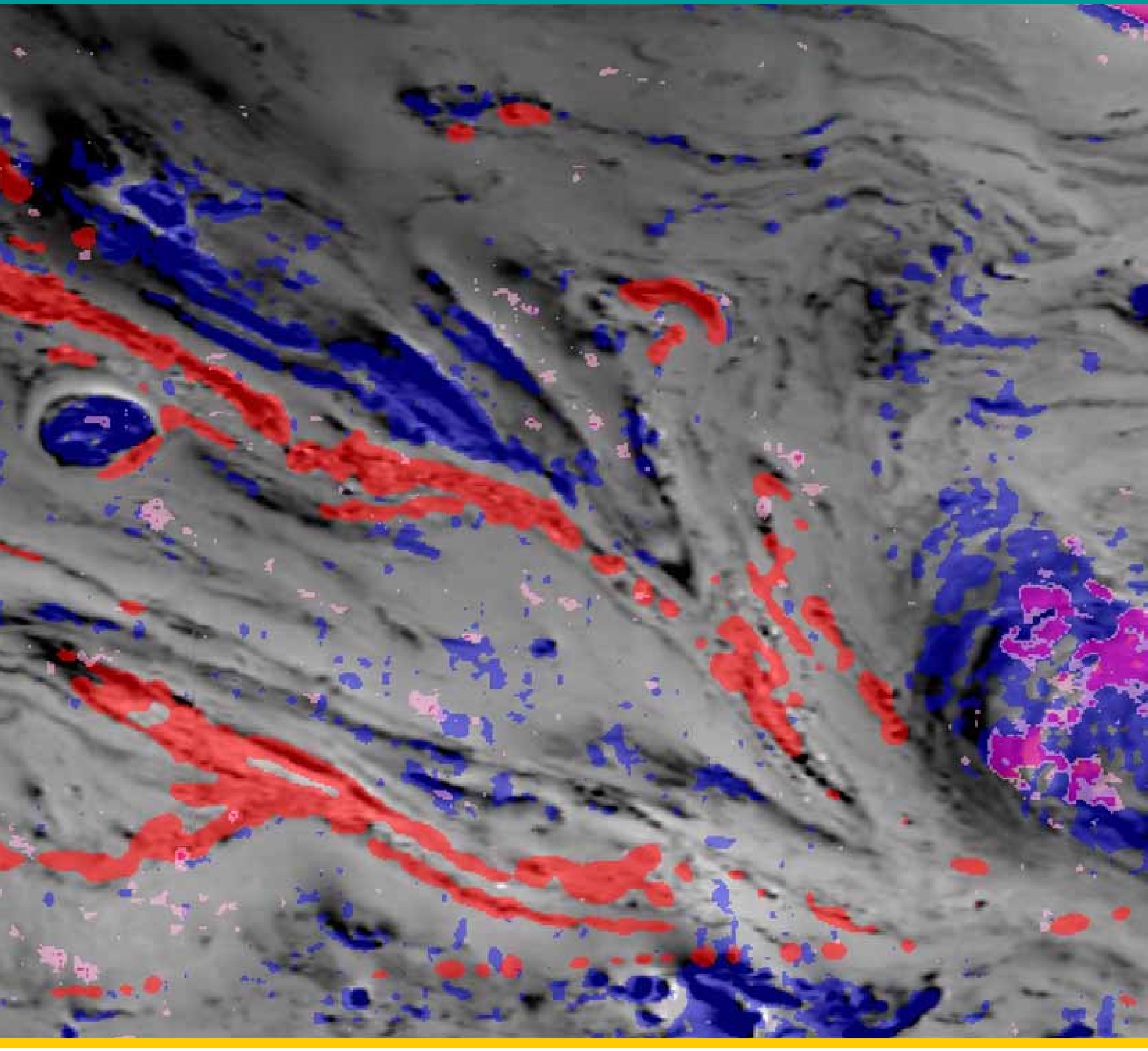

Tips and tools for the application of GTK's airborne geophysical data

Meri-Liisa Airo, Eija Hyvönen, Jouni Lerssi, Hanna Leväniemi and Aimo Ruotsalainen

GEOLOGIAN TUTKIMUSKESKUS

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Unless otherwise indicated, the figures have been prepared by the authors of this article. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

Front cover: A combination of GTK's airborne geophysical datasets from the Rovaniemi schist belt, northern Finland: magnetite-bearing rock units in blue, high-potassium units in purple and sulphide-bearing units in red.

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Airborne geophysical surveys cover the whole of Finland and offer high-resolution magnetic, radiometric and electromagnetic datasets for various geo-scientific applications. This short 'user guide' provides background methodology, or 'tips and tools', to improve the extraction of geological information from the multivariate airborne geophysical data. The efficient use of these datasets is promoted by knowledge of data acquisition and processing, data quality limitations and, in particular, assessment and understanding of the possible sources of geophysical anomalies. We discuss the methods and techniques for practical geological interpretation, particularly in the context of regional interpretation. We introduce basic concepts for bedrock and soil mapping, and case studies introducing integrated interpretation and prospectivity analysis for mineral potential purposes.

Keywords (GeoRef Thesaurus, AGI): geophysical methods, airborne methods, interpretation, models, bedrock, soils, mapping, mineral exploration, Finland

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Geofysikaaliset lentomittausaineistot pitävät sisällään korkealaatuiset, koko Suomen kattavat magneettiset, radiometriset ja sähkömagneettiset tietoaineistot käytettäväksi mitä moninaisimmissa geotieteellisissä sovelluksissa. Tämä 'käytön opas' tarjoaa taustatietoa – 'vinkkejä ja välineitä' – näiden tietoaineistojen tehokkaaseen hyödyntämiseen sekä kuvaa tietojen hankkimisen ja prosessoinnin käytäntöjä ja datan laaturajoituksia. Tavoitteena on tuottaa lentogeofysikaalisesta monimuuttuja-aineistosta entistä monipuolisempaa ja sisällöltään tarkempaa geologista informaatiota. Raportissa käsitellään lentomittausaineistojen tulkinnan perustekniikoita kallioperän ja maaperän kartoitukseen sekä käydään läpi geologisen mallinnuksen menetelmiä erityisesti alueellisesta näkökulmasta. Mukana on myös esimerkkejä integroidusta tulkinnasta ja prospektiivisuusanalyysistä mineraalipotentiaalin kartoitukseen.

Asiasanat (Geosanasto, GTK): geofysikaaliset menetelmät, lentomittaukset, tulkinta, mallit, kallioperä, maaperä, kartoitus, malminetsintä, Suomi

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CONTENTS

1 INTRODUCTION

The Geological Survey of Finland (GTK) conducted a long-term airborne geophysical survey programme, starting in the early 1970s and ending in 2007, with the goal to create a consistent, country-wide airborne geophysical database. The multi-parameter surveys included magnetic, electromagnetic and gamma-ray spectrometric measurements systematically performed at a line spacing of 200 m and with a nominal terrain clearance of 30 m. The simultaneous recording of these three data sets provided a remarkable, renewable data supply for exploration, regional bedrock mapping and environmental studies. The high resolution of the data allows interpretation and modelling at both regional and local scales. This 'user guide' is intended to promote and customize the use of these datasets for different geo-scientific applications and provides background methodology - 'tips and tools' - for extracting geological information from airborne geophysical data. The structure of this report is organized so that each section can be separated from the context and considered individually. This is why repetition of some of the issues could not be avoided.

This user guide first describes matters concerning data properties and quality in terms of data acquisition and processing. Specific issues for electromagnetic, magnetic and radiometric data are discussed. The most common techniques for the enhancement, transformation and filtering of airborne geophysical datasets are briefly reviewed. We also introduce a series of useful products, such as the 'interpretation package', or pseudo-geological maps, for a first-pass geological and geophysical analysis of areas under investigation. The lithological characterization and structural interpretation of bedrock are represented by different case studies. Basic concepts for application in soil mapping and environmental studies are also included. In the final part of this guide, we provide examples of the integration of geophysical data with other geological information in analysing potential areas for different mineralization styles.

Initially, the exploration of massive sulphide deposits was one of the main objectives of GTK in starting systematic airborne geophysical surveys in Finland. This is also why the electromagnetic fixed-wing frequency-domain method was developed and constantly improved during the course of the survey programme. The efficiency in mapping near-surface conductivity contrasts in bedrock and overburden, and the country-wide coverage are benefits of this method, although the depth penetration is limited to the shallow subsurface (down to ~100 m at best). Here, we introduce the techniques and means to best use these data for the Finnish terrain.

Mineralization-related geophysical signatures may be either strong or very subtle, or they may cover or disturb each other. The search for anomalous signatures that are possibly related to a certain mineralization type may be accelerated by the integration of multivariate geo-scientific datasets in interpretation. The use of appropriate processing of airborne geophysical data provides a more profound understanding of key geophysical parameters for detecting and identifying interesting targets. A systematic approach using spatial analysis techniques, such as principal component analysis or unsupervised classification, often reveals information that is not readily evident when using conventional procedures.

2 AIRBORNE GEOPHYSICAL DATA IN FINLAND

2.1 Datasets

Finland was covered with systematically collected airborne geophysical data at a nominal flight altitude of 30 m and a line spacing of 200 m during 1972–2007, resulting in datasets with a very high resolution. At the end of the survey programme, approximately 1.9 million line-kilometres had been completed, a task that spanned over three decades. The data acquisition and processing were performed using digital formats and technologies from the beginning. Electromagnetic devices were developed and added to magnetometers and gamma-ray spectrometers. Regional geological mapping greatly benefitted the three geophysical datasets, and a comparison of these datasets with the lithology is presented in Figure 1. For more information on the data acquisition systems and data processing, see Hautaniemi et al. (2005) and Moore (2008). The maintenance, archiving and modelling of airborne geophysical data have also been briefly reviewed by Airo et al. (2011).

The country-wide processed dataset is available in two digital formats: numerical data at the original sampling intervals along the true flight lines in ASCII format, and interpolated grids with a 50-m cell size. The airborne geophysical data are included in GTK's mineral reserve service, accessible via: http://gtkdata.gtk.fi/MDaE/index.html. Additional information is available by contacting Eija Hyvönen (eija.hyvonen@gtk.fi).

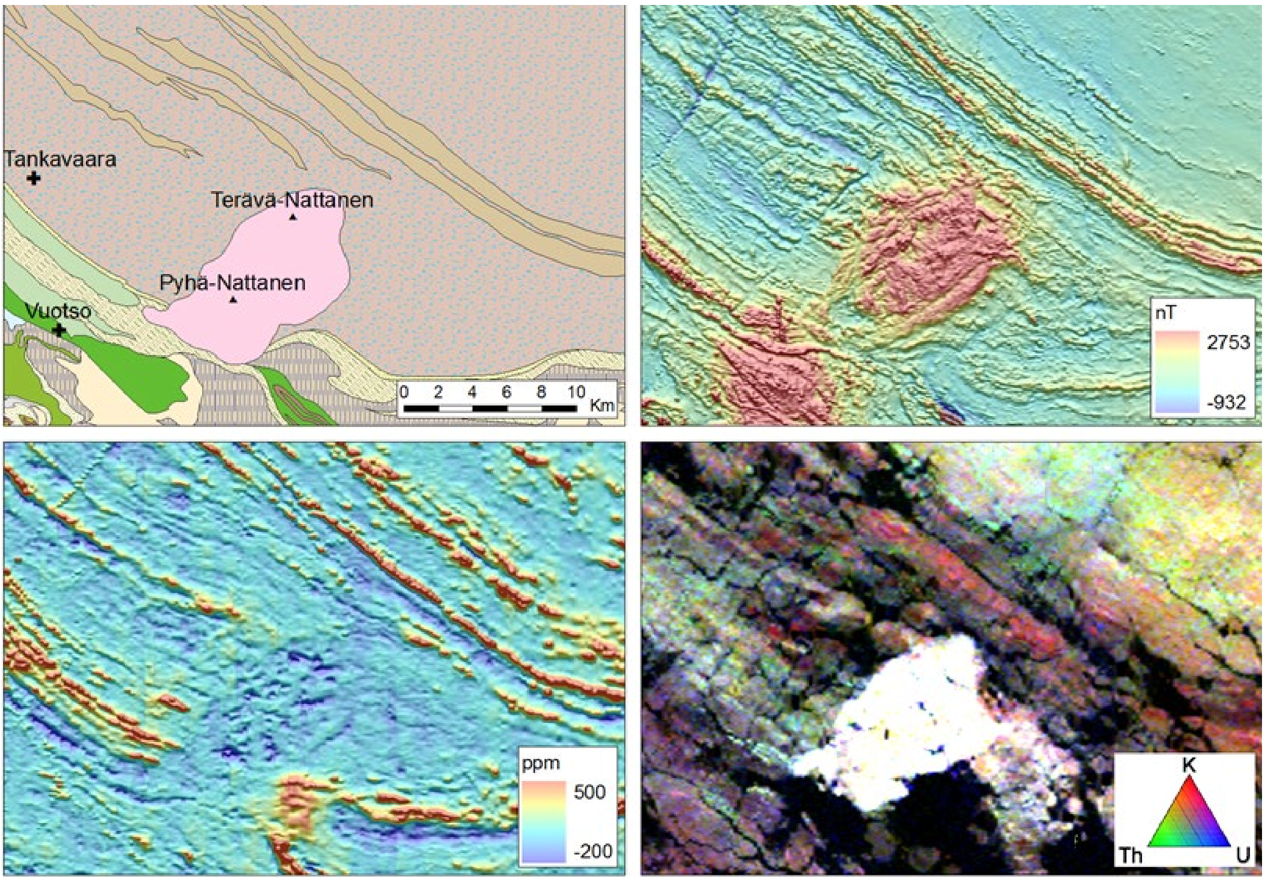


Fig. 1. An example of GTK's airborne geophysical datasets compared with lithology. The maps display plutonic rocks (pink = granitoids), intruding garnet-cordierite gneisses of the Lapland granulite complex (brownish); green = amphibolite (source DigiKP Finland; 14.10.2014). Upper left: Lithological map. Upper right: Magnetic map. Lower left: Electromagnetic map, 3 kHz in-phase response. Lower right: Radiometric ternary image.

2.2 Data Quality and System Characteristics

As airborne geophysical data were collected for over 35 years, it is understandable that the technologies and processing methods have developed and varied over these years. In particular, the quality of the early data is sometimes moderate because of the technology limitations, and has required re-correction that is currently ongoing and being updated by GTK. In our procedure, the data are not re-levelled by any smoothing method, but the actual previous processing errors are corrected, thereby preserving all the original information in the data. For radiometric data, the re-correction includes system sensitivity coefficient analysis for each year and each flight area. The re-correction of electromagnetic data concerns zero levels and calibrations consistently checked and corrected throughout the country. Work still remains with the poor calibrations of the oldest data, and the whole dataset requires more fine-tuned levelling. Re-correction of the entire magnetic dataset comprises re-levelling of the data and the checking of some secular corrections.

Despite the quality issues, the country-wide datasets still provide an excellent regional overview of any area of interest. However, for detailed studies, it is always better to go back to the original data. Here, we list some of the issues (concerning both data quality and system-characteristics) that can affect the interpretation and should be taken into consideration:

1. Equipment. Three different aircraft, two electromagnetic coil orientations, several magnetometer configurations and different gamma-ray spectrometer crystal volumes were used in the data collection. This all presents a challenge when combining the data. The amount of data is enormous, comprising 300 flight areas and 1.9 million line-kilometres of data. The country-wide maps have annually been added to, with each addition being a result of contemporary best knowledge of calibration and data processing procedures. Thus, levelling errors between and within various flight areas are currently still unavoidable.

2. Navigation, positioning and other coordinate issues. Before the differential GPS era (1993–2007), navigation and positioning was solely carried out using aerial photograph fix points (1973–1975) or in combination with a Doppler system (1976–1992). Positioning errors may occur in the pre-GPS data and are almost impossible to correct afterwards. Some other, more local coordinate issues mainly caused by data clipping and/or joining procedures may also occur, especially in the vicinity of the borders of the individual survey areas.

3. Issues specific to electromagnetic data:
   a. Calibrations and levelling errors. The calibration of the older data is not up to current standards. There are also still some line-to-line (as well as area-wide) levelling errors in the data.
   b. Noise levels. Noise in an electromagnetic system can result from various sources, such as technical issues (e.g. soldering or contacts of joints) or the weather (e.g. thunder, rain, high wind). Some areas of the country-wide electromagnetic dataset are visibly noisy. The noise may not, however, be present at all the frequencies, even if it appears in the 3-kHz country-wide map, so it may be worthwhile to check all the other frequencies (if available) from these areas.
   c. Electromagnetic response to high susceptibility. In the case of low conductivity and high magnetic permeability (i.e. susceptibility), the electromagnetic system becomes sensitive to the magnetic response. This response is in phase with the transmitter signal and opposite in sign to the conductivity response. Thus, the susceptibility effect will show as a negative response in the in-phase (real) component in areas of low conductivity. It should be noted that in areas of high conductivity, the effect is still present but masked by the high-conductivity response. The negative response is present in the original data and in calculations of the *Re/Im* ratio (the ratio of the *Re*al to the *Im*aginary component), but not in the apparent resistivity data.
   d. Using apparent resistivity maps as 'true' resistivity maps. An apparent resistivity map is a calculation based on a homogeneous half-space model. This means that at every point we make an assumption that the ground beneath the point has constant

conductivity. This is very seldom true, especially in the complex geology of the Finnish bedrock. The apparent depth is an even more ambiguous parameter and should only be used as a guideline. Moreover, calculation of the apparent resistivity does not account for the susceptibility response, and in areas with high magnetic permeability will consequently give excessively high resistivity values. It does, however, provide a good qualitative regional approximation of the resistivity distribution, although for detailed inspection it is always better to check and remodel the original data. For a regional alternative, the simple Re/Im ratio of the real to the imaginary (or 'quadrature') components of the electromagnetic data can be used, as this is easier to control and understand (and also takes the susceptibility effect into account).

e. Electromagnetic sensitivity to flight altitude. An electromagnetic signal attenuates as a function of the survey altitude. This can be readily seen (especially in more resistive areas) when comparing the signal with the flight altitude on flight profiles. Although a crucial issue in data inversion, this fact also needs to be taken into consideration in more qualitative interpretation.

4. Issues specific to magnetic data:
   a. Levelling issues within survey areas. In particular, 'heading error corrections' (errors that are dependent on the flight direction and usually affect entire flight lines) were not up to current standards in the early stages of the airborne mapping programme, and some errors still remain in the data. Furthermore, with multi-magnetometer systems, the levels between various magnetometers may not be properly corrected in some areas.
   b. Secular corrections. The earth's magnetic field is slowly changing due to core processes. These changes were compensated for in the surveys by correcting the general levels to match a reference model representing the field at a certain time (the IGRF model). Due to inaccuracies in this secular correction over the years, some levelling errors exist between adjacent survey areas. However, the inaccuracies in the secular correction do not affect the short-wavelength (local) magnetic anomalies, but only the general level of the flight area's dataset.
   c. Data gaps. A characteristic of proton magnetometers (used 1973–1991) is that they perform poorly in the case of a high magnetic gradient. This is rather inconvenient, as there are some data gaps at the sides of some of the most interesting strong anomalies. These data gaps are generally very short, however, and have little effect on the regional interpretation.
   d. An automatic compensation procedure that eliminates the effects of aircraft movement from the magnetic data was not utilized until 1992. In the earlier data, there may be some data distortions due to aircraft movements, but these are generally very small both in amplitude and wavelength.
   e. Interpolation procedures. Various interpolation procedures were in use during the 35 years of the mapping programme. The country-wide dataset is a mixture of these. When strictly uniform data are needed, it is better to re-interpolate the original line data.

5. Issues specific to radiometric data:
   a. Radon correction. Natural radon emission affects gamma-ray surveys, although mostly the uranium component. This error source was corrected during the last decade of the mapping programme (1997–2007), but so far, no radon correction has been applied to the earlier data. Thus, some levelling error may remain in the uranium component as a result of incomplete radon correction.
   b. The Chernobyl accident (1986) introduced man-made radiation that can also be seen in the airborne measurements. The data most affected are from Central Finland during 1986–1990.
   c. As radiometric data are highly sensitive to moisture (water very effectively attenuates the radiation), the survey areas flown either in spring or autumn suffer from moisture attenuation more than those flown in midsummer. These effects can be corrected with area-wide levelling, but the procedure has not yet been applied to the data.
   d. Other levelling issues. Radiometric data undergo a series of correction procedures and calibrations, and although well-defined for later data, the corrections for earlier data

may not be up to current standards. The variation in data correction procedures results in levelling errors that are especially notable in the calculated ratio datasets.

e. Source–detector response. Radiation from narrow sources attenuates more rapidly than that from broader ones. An increasing distance to the source results in a reduced signal-to-noise ratio, because the radiation signal decays at an exponential rate. During airborne surveys, the terrain clearance varies from one flight line to another (the flight height is not constant). A higher flight altitude increases the field of view (footprint) of the spectrometer, thereby reducing the resolution of discrete sources. Because of the statistical (stochastic) nature of gamma radiation, a limited time of registration may cause high uncertainty in the results.

3 INTERPRETATION OF AIRBORNE DATA: BASIC CONCEPTS

3.1 Interpretation Workflow

Airborne geophysical data provide the basis for a wide range of geological and geophysical interpretation and modelling applications at both regional and local scales. The applications include geological mapping and mineral exploration, bedrock and soil mapping for natural resource exploration and evaluation, and interpretation for environmental and engineering requirements. In all types of applications, the first step is to gain an overall geologically reasonable picture of the area under investigation, the 'big picture', based on regional geophysical data. The big picture will contain some uncertainties and pose some questions about the reasons for geophysical anomalies. Indicative petrophysical properties help to characterize the source rocks of the anomalies. They are also important when modelling the geometry and dimensions of the anomaly sources. Different advanced processing methods provide tools for understanding both the regional distribution and the trends in geophysical properties to be related to near-surface and subsurface geology. The selection between different enhancement and transformation techniques depends on the geological question of interest.

The geophysical interpretation process can be described by the following steps:

1. The big picture – a preliminary geological model
   - re-evaluation of the existing geological and geophysical data
   - analysis of regional geophysical data
2. Estimating subsurface geology
   - advanced processing & data integration
   - crustal-scale forward modelling and inversion
   - petrophysical properties
   - depth to basement modelling
   - 3D visualization
3. Integrated analysis at the lithological to deposit scale
4. Exploration or other implications.

3.2 Interpretation Package

Here, we introduce the interpretation package as a first-step tool for geological modelling. Thematic maps of this interpretation package depict the variation in geophysical properties and outline geophysical provinces in the area under investigation. Combination of the different thematic geophysical maps represents a type of pseudo-geological map that can be used in preliminary geological interpretation (explained in more detail in Section 4.3). The most important issues in the geological enigma are the lithology, structural elements, and the relationship between structures and geological units. Estimates of the lithology/rock type are benefitted by knowing whether the rock is electrically conductive, what the radioelement distribution is, and what type of magnetic signature it has. Magnetization reflects the content and distribution of magnetic minerals in rock. These questions can be resolved by investigating different geophysical datasets (see clarification of different techniques in Section 3.3):

- magnetic field intensity, magnetic classification

and the magnetic anomaly signature;
- magnetic patterns for outlining and evaluating the structural elements;
- the distribution of electrically conductive ground (bedrock or soil);
- classification of radioelement distribution.

3.3 Techniques Used in Interpretation

Potential field datasets provide useful information on the distribution of both density and susceptibility/remanence (gravity and magnetic data, respectively) and also on the depth of the anomaly source. Various enhancement methods are commonly used in order to obtain qualitative information and rapid estimation of the structures at the regional scale. The same methods can also be used at the local (target) scale, but modelling and inversion are usually used to gain more accurate results.

MAGNETIC DATA

As magnetic interpretation is inherently ambiguous and sensitive to magnetic inclination, it is usually recommended that the data be transformed to match the vertical inclination (reduction to the pole, RTP). In Finland, the inclination varies around 75 degrees, and as the effect of RTP transformation is rather small it is not commonly used. Furthermore, the transformation is based on the assumption of induced magnetization only, so if remanent magnetization is present, the results are not reliable. However, it is still good practice to use RTP transformation, at least for anything but very large-scale interpretation.

Various general enhancement and filtering techniques are used, including:
- various (grey scale or colour scale) grid shading relief techniques;
- wavelength filters: high-pass and band-pass filters for separating local (shallow) anomalies or low-pass filters for separating regional (deeper) anomalies, edge detection techniques;
- directional filters to emphasize a particular direction in structural interpretation;
- upward-continuation for noise reduction or for eliminating the short wavelength structures or enhancing deeper parts of the anomaly source.

Structural interpretation techniques mainly include various adaptations of magnetic derivative calculations. In regional scale studies, the most common filters for raster data are as follows (see examples in Fig. 2):
- First or higher order derivatives in any direction, most commonly along the main coordinate axis (X, Y, Z).
- The analytic signal. Less dependent on the field inclination or dip of the source. The maximum of the analytic signal is located over a susceptibility contrast (anomaly source body contact), and the width of the maximum is relative to the depth of the contact.
- The total horizontal derivative. The maximum of the derivative is located over a vertical source body contact. In the case of a dipping contact, the maximum is located along the dip. Depends on the inclination of the field, so RTP transformation is recommended.
- The tilt derivative and its total horizontal derivative. The tilt derivative depends on the inclination, whereas its total horizontal derivative does not. The tilt derivative equalizes the total field amplitudes and thus emphasizes structural features. The tilt derivative is in fact an angle parameter and its values vary between $-\pi/2$ and $\pi/2$, the zero contours locating close to the source–body contact. The horizontal derivative of the tilt derivative is independent of inclination and (similarly to the analytic signal) its maximum is located over a source–body contact.

Structural analysis can be further extended to source body depth investigations. Among different methods for interpreting the subsurface geometry of geological units, the following techniques have been used, for instance, in GTK's interpretation projects (below, we introduce case examples from Tanzania and Kosovo, where GTK's 3-in-1 survey system, similar to that in Finland, was adopted):
- Euler deconvolution: a semi-automated method for depth estimation;
- Local wave number of source parameter imaging (SPI): a grid-based method for estimating the depth of the magnetic source.

In the northern magnetic hemisphere, the top of a simple body with magnetic susceptibility causes a positive anomaly and its bottom causes a nega-

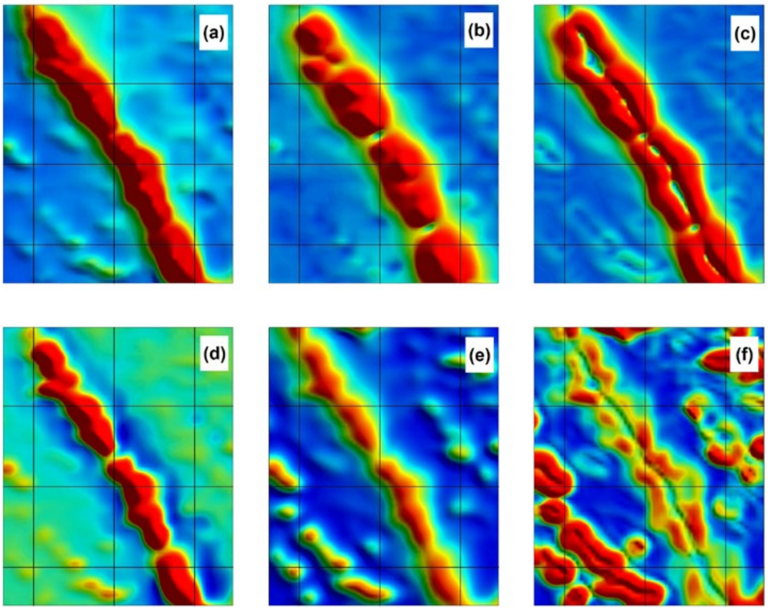


Fig. 2. Different filters for raster data. The location of the data window is indicated in Figure 11a.

a) Total magnetic intensity (TMI), reduced to the north magnetic pole.
b) Analytical signal of TMI (AS).
c) Horizontal derivative of TMI (dxy).
d) First-order vertical derivative of TMI (dz).
e) Tilt angle of the total derivative of TMI (TDR).
f) Horizontal derivative of TDR (HD_TDR).

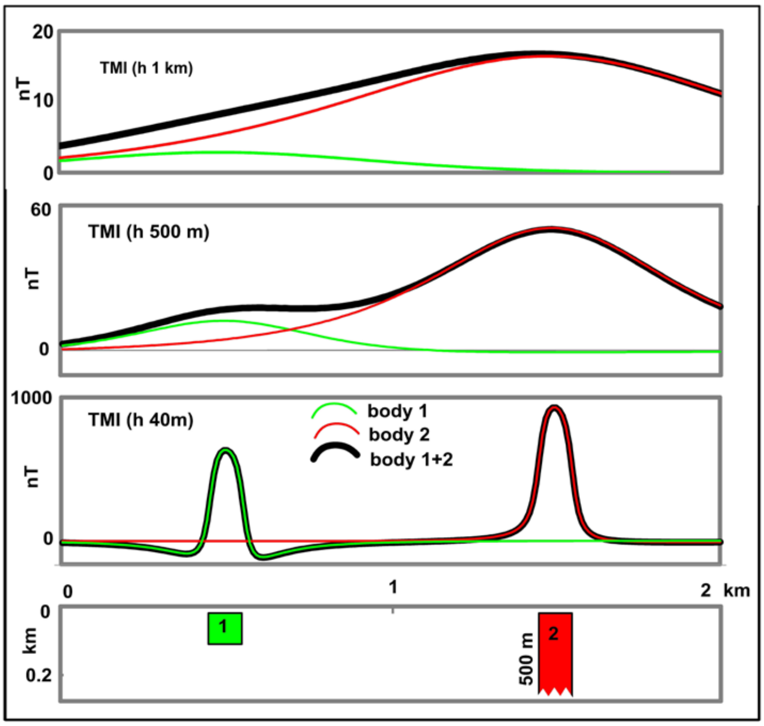


Fig. 3. Upward continuation of magnetic data. The effect of the source depth on the magnetic anomaly is illustrated by two theoretical bodies.

tive anomaly in the magnetic measurements. The total measured anomaly is the sum of these two components. When the depth extent of the body increases, the contribution of the negative anomaly component decreases until it finally has no real influence on the measurements.

If the observation elevation increases, the anomalies of shallow bodies cannot be seen in the measured total magnetic intensity (TMI). The elevation of measurement can be simulated by continuing the measured magnetic data upwards (Fig. 3).

ELECTROMAGNETIC DATA

Airborne multi-frequency electromagnetic surveys respond to conductive material in the geological section, with a maximum penetration depth of 70–100 m, depending on the overall resistivity of subsurface. The composition and thickness of the overburden, the nature and degree of weathering, surface water and groundwater, the geomorphology and bedrock exposure all affect the resistivity. The measured electromagnetic response function depends on a) the dimensions of the measurement system and the source (geometry, size, position) and b) the measurement frequency and the electrical properties of the source. The in-phase (real) and quadrature (imaginary) parts of the response function can be drawn as a function of the response parameters (see the in-phase response curves in Fig. 4). The interpretation guidelines of GTK's electromagnetic system have been reported by Suppala et al. (2005) and, especially in the context of the 4-frequency system, by Leväniemi et al. (2009).

Electromagnetic data are useful in high-resolution mapping of shallow mining targets and environmental disturbances. Under suitable geological conditions, radiometric data and the apparent resistivity can complement one another in the characterization of the near-surface geology. The greatest correlation with radiometric data is obtained from electromagnetic data measured at a high frequency (GTK system: 24510 kHz). The in-phase component helps to distinguish subsurface conductivity structures, especially at low frequencies (GTK system: 912 kHz or 3005 kHz). The quadrature (imaginary) component describes surface conductivity, and is commonly related to the overburden. The apparent resistivity, calculated from the real and imaginary components, is good for imaging weak conductivity or conductivity structures, for near-surface geological and environmental applications.

High magnetic permeability (susceptibility) may produce the so-called susceptibility effect verified by a negative in-phase response in frequency-domain electromagnetic data (Huang & Fraser 1998, 2000). The negative in-phase response caused by high magnetization at low conductivities is seen in all four frequencies of GTK's system (Fig. 4, Leväniemi et al. 2009). This effect is very useful when separating source rocks bearing either magnetite or the ferrimagnetic pyrrhotite. The electromagnetic ratio *Re/Im* (abbreviation of *Re*al/*Im*aginary) has successfully been used in the classification of ground conductivity and to obtain information on the type of magnetic mineral in rocks acting as the anomaly source. Pyrrhotite-bearing anomaly sources can generally be distinguished by their high conductivity combined with their magnetic signature.

Electromagnetic data are sensitive to noise from different sources. The appropriate noise level allowed depends on the scale of the study. Noise and levelling errors can be smoothed, e.g., by cut-off, highpass or bandpass filtering. Figure 5 compares three different processing results for an area in western Finland.

In summary, practical methods for utilizing electromagnetic datasets include:

- the response function and classification,
- the electromagnetic ratio *Re/Im*,
- the combination of high and low frequencies / real and imaginary components,
- the susceptibility effect (negative real response at low conductivity).

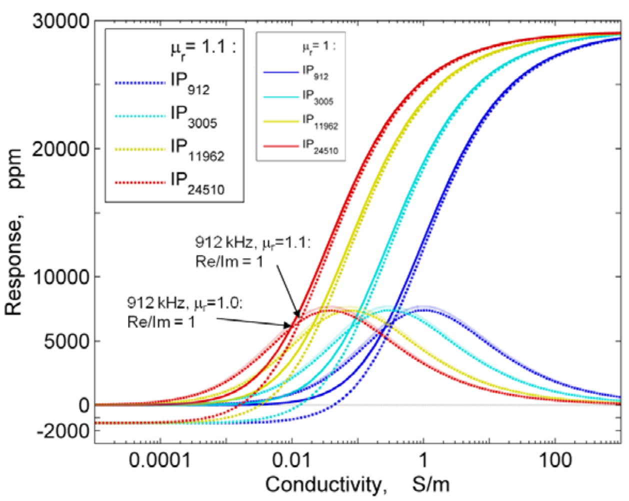


Fig. 4. Electromagnetic response curves for GTK's four-frequency data (from Leväniemi et al. 2009). IP = in-phase (the real) component; μ_r = magnetic permeability (SI).

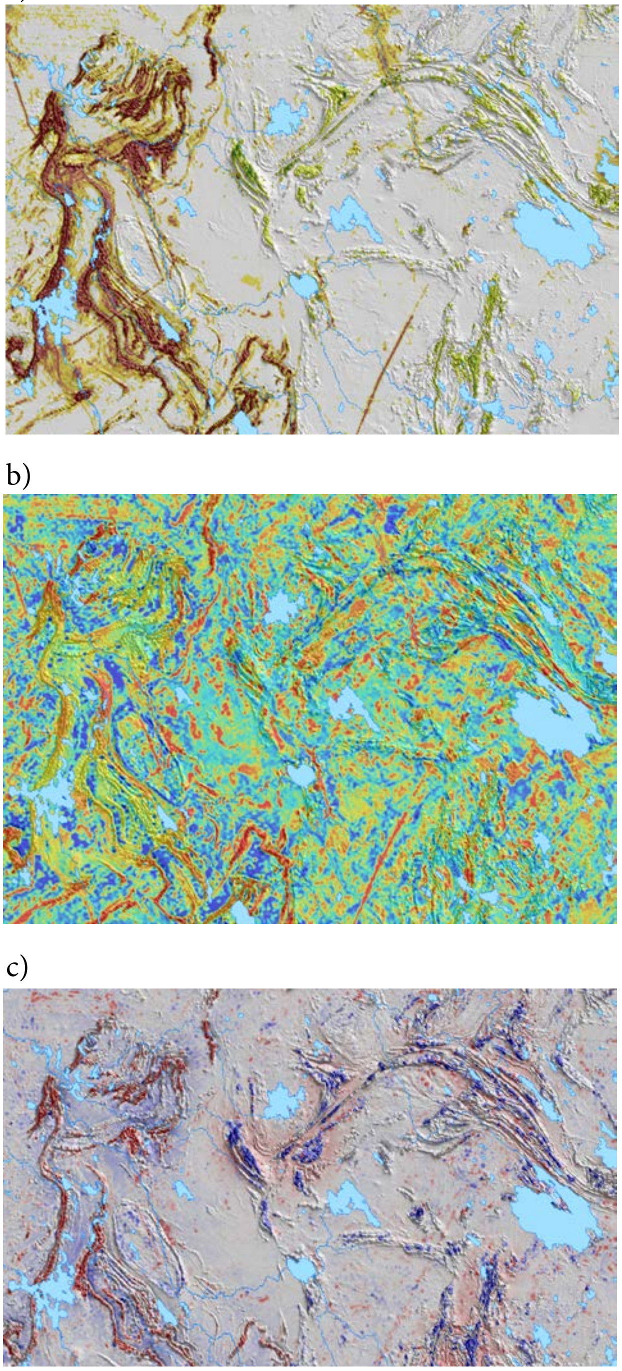
a)
b)
c)


Fig. 5. Examples of processed electromagnetic data for qualitative interpretation. The map area is 70 km wide. Contains data from the National Land Survey of Finland Topographic Database 03/2013. a) In-phase (real) component (cut-off ± 100 ppm). Red-brown units are good electrical conductors and green units denote magnetite-bearing rocks. b) Apparent resistivity, highpass-filtered. Red = low resistivity, blue = high resistivity. c) Re/Im ratio (Ratio of the Real to the Imaginary component), bandpass-filtered 500–10 000 ppm. Red = good conductors, blue = negative values of real component (denotes magnetite-bearing units).

RADIOMETRIC DATA

The majority of gamma radiation originates from potassium (^{40}K) and the decay series of thorium (^{232}Th) and uranium (^{238}U). Felsic rocks have a significantly higher radioelement content compared to those of mafic and ultramafic rocks. Sedimentary rocks reflect the content of their source rocks, and thus the sediments derived from granitic source rocks may have quite a high radioelement content, whereas the mature (orthoquartzitic) sediments may be expected to have much lower values. Metamorphism does not affect the radioelement content unless metasomatic or hydrothermal alteration has taken place (Dickson & Scott 1997).

In GTK's airborne radiometric surveys, where the nominal flight altitude was 30 m, the measurement-'footprint' approximately corresponds to an ellipsoidal area with a radius of 120 m, giving radionuclide distributions across the landscape. The resolution along flight lines is much better than that between the flight lines, and it rapidly declines with lateral distance from the flight line. In Finland, the use of radiometric data is controlled by 1) signal attenuation because of soil moisture and surface waters, 2) the strong effect of artificial radiation due to fertilized fields in southern Finland, 3) enhanced radiation from uranium in the surroundings of peat farms, and 4) glacial debris and dispersion. The possible relationships between high-resolution radiometric data and certain soil properties must be understood before interpretations are made about the mineralogy and geochemistry of the parent material. Figure 6 provides an example of the integrated use of cut-off radiometric thorium data with electromagnetic classification (apparent resistivity calculated from the 25 kHz frequency data). Different parts in terms of weathering of the source intrusion are highlighted. Regions of high thorium radiation and low resistivity are more highly weathered than their surroundings.

In summary, techniques useful in interpretation include the following:

- Ratios (K/Th, U/Th, K/U) may describe geological units and minimize the effect of soil moisture. In the weathering of rocks, K is soluble and mobile, while U and Th are less mobile. Ratios of U/Th and U/K are consequently useful in soil studies.

- Normalization helps to distinguish variations in radiation signatures of different geological provinces.
- Filtering or cut-off techniques may be used to improve the signal-to-noise ratio.

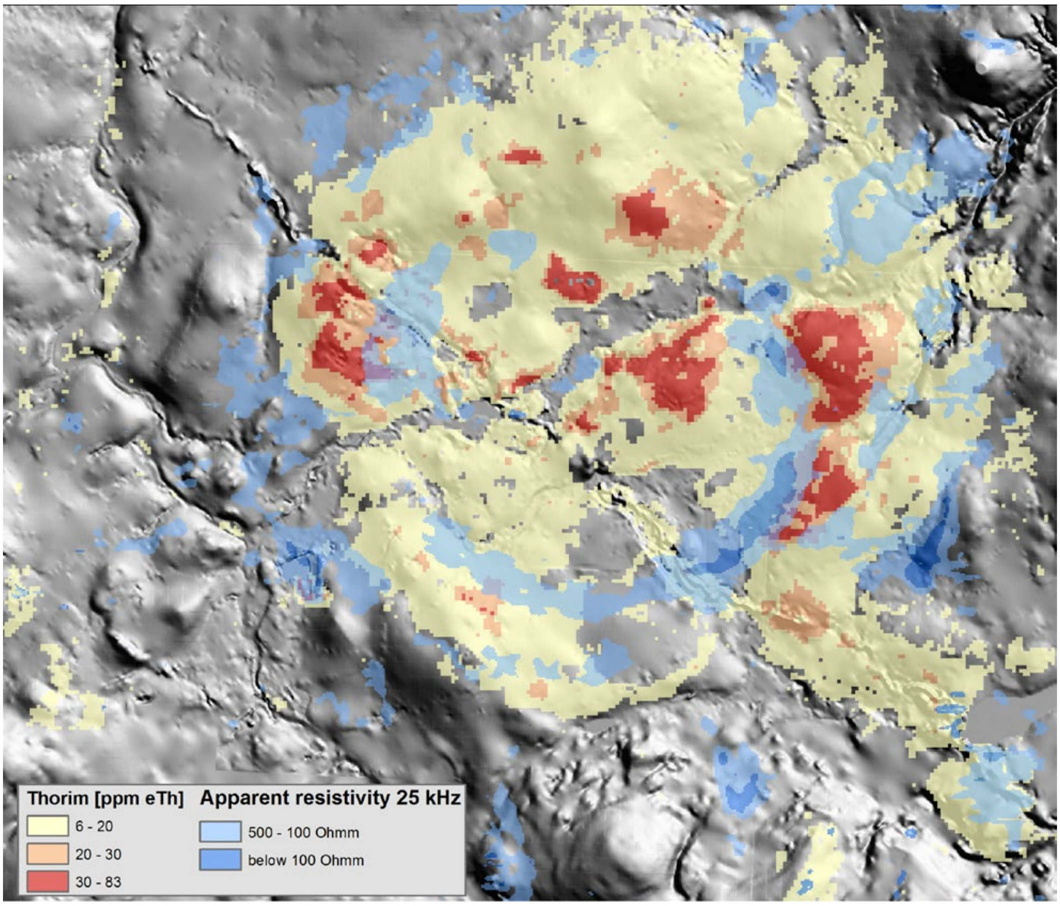


Fig. 6. Combination of GTK's processed radiometric and electromagnetic data indicating variously weathered parts of the Sokli carbonatite intrusion, northern Finland. Background map: digital elevation model (grey).

4 BEDROCK MAPPING

4.1 Introduction

GTK's airborne geophysical data have played a key role in bedrock mapping in Finland. Through the years, airborne surveys have been carried out in a systematic manner in order to construct a consistent database. Magnetic surveys record the variation in total magnetization, which is comprised of two components: induced and remanent magnetization. The induced magnetization component depends on the concentration of magnetic minerals in the rock, whereas remanent magnetization is comprised of several magnetization components acquired at several stages during the rock's history. Gamma-ray spectrometric surveys measure the concentration/distribution of radioactive elements: potassium, thorium and uranium. The frequency domain electromagnetic system was developed to map the 3D variation in near-surface conductivity, and to search for conductive metallic sulphides and oxides in practically resistive host rocks. This type of '3-in-1' approach, with detailed measurements at a low altitude, has resulted in a number of datasets introducing different characteristics of the bedrock and its overburden. They contain an enormous amount of geological information waiting to be utilized in geological investigations. Knowledge of physical property contrasts associated with specific rock types greatly improves geological characterisation. GTK provides a country-wide petrophysical data collection with information on the rock density and magnetic properties of different Precambrian rock types (i.e., Airo 2005, Korhonen et al. 1997, Airo & Säävuori 2013).

Geophysical data analysis can be focused on various aspects in geological mapping and structural analysis:

- *Lithological units* can in a broad sense be outlined because of the typical geophysical properties of different rock types. The relative proportion and distribution of various rock-forming and accessory minerals, differing in their physical properties and mineral texture, give reason to distinguish rock units according to their magnetic, electromagnetic and radiometric responses.
- *Structural features* such as faults, contacts, dips or dimensions can be interpreted and mapped. Traditional tools aiding in the interpretation include magnetic derivatives, frequency filters or upward continuation. Structural provinces can be outlined by their characteristic magnetic patterns or trends, or 'homogeneously' irregular magnetic patterns. This is because in any particular geological setting, the formation conditions were similar during the period when magnetic minerals (magnetite, ferrimagnetic pyrrhotite) were formed. This also applies to the formation of minerals that are electrically conductive (graphite and sulphides), resulting in continuous magnetic or conductivity anomalies.
- *Chemical alteration or weathering* may change the rock mineralogy, and these changes in turn alter the geophysical properties of rock. Detailed examination of airborne geophysical data, particularly radiometric and high-frequency electromagnetic data, may reveal regions of altered mineralogy.
- *Separation of deep or shallow anomaly sources* is possible by inspection of short- and long-wavelength magnetic anomaly data. Low-frequency electromagnetic anomalies correspond to deeper anomaly sources (only down to ~100 m). Shallow or at-surface sources are recognized by electromagnetic high-frequency, radiometric and magnetic short wavelength data. Petrophysical sampling from outcrops is of great help.
- *The age relationship* between geological units, bodies or structures may be interpreted by the examination of adjacent or crosscutting geophysical anomaly patterns or by specific magnetic investigations of the natural remanent magnetization or the anisotropy of magnetic susceptibility.

4.2 Case Study: Lithological Characterization

The geophysical provinces of Pirkanmaa and Vammala regions in southern Finland were characterized on the basis of airborne magnetic, radiometric and electromagnetic data (Airo & Leväniemi 2012). The interpretation results can be combined as a 'litho-geophysical' map and the geophysical provinces can be attributed to different lithological units. Figure 7 presents the lithological units in the area and the corresponding geophysical maps. The Pirkanmaa migmatite suite in the middle of the study area is distinguished by short-wavelength, local magnetic anomalies combined with increased conductivity caused by graphite- and/or sulphide-bearing rocks. The surrounding volcanic belts are characterized by wide, intensive magnetic anomalies caused by magnetite, as indicated by the negative response in the electromagnetic data. Electrical conductors were classified on the basis of electromagnetic data. The apparent resistivity data do not discern the negative response in the real component, whereas using the Re/Im ratio, the magnetite-bearing units can be distinguished. The radiometric data is only locally attributed to exposed bedrock because of the covering and attenuating effect of the overburden, but the granitoids show high uranium and potassium contents in parts. In particular, various granitoid units in the study area can be differentiated from each other based on their prevalent potassium or uranium radiation values. Thorium radiation in the study area is largely related to the clayish fields in the central-southern part of the map.

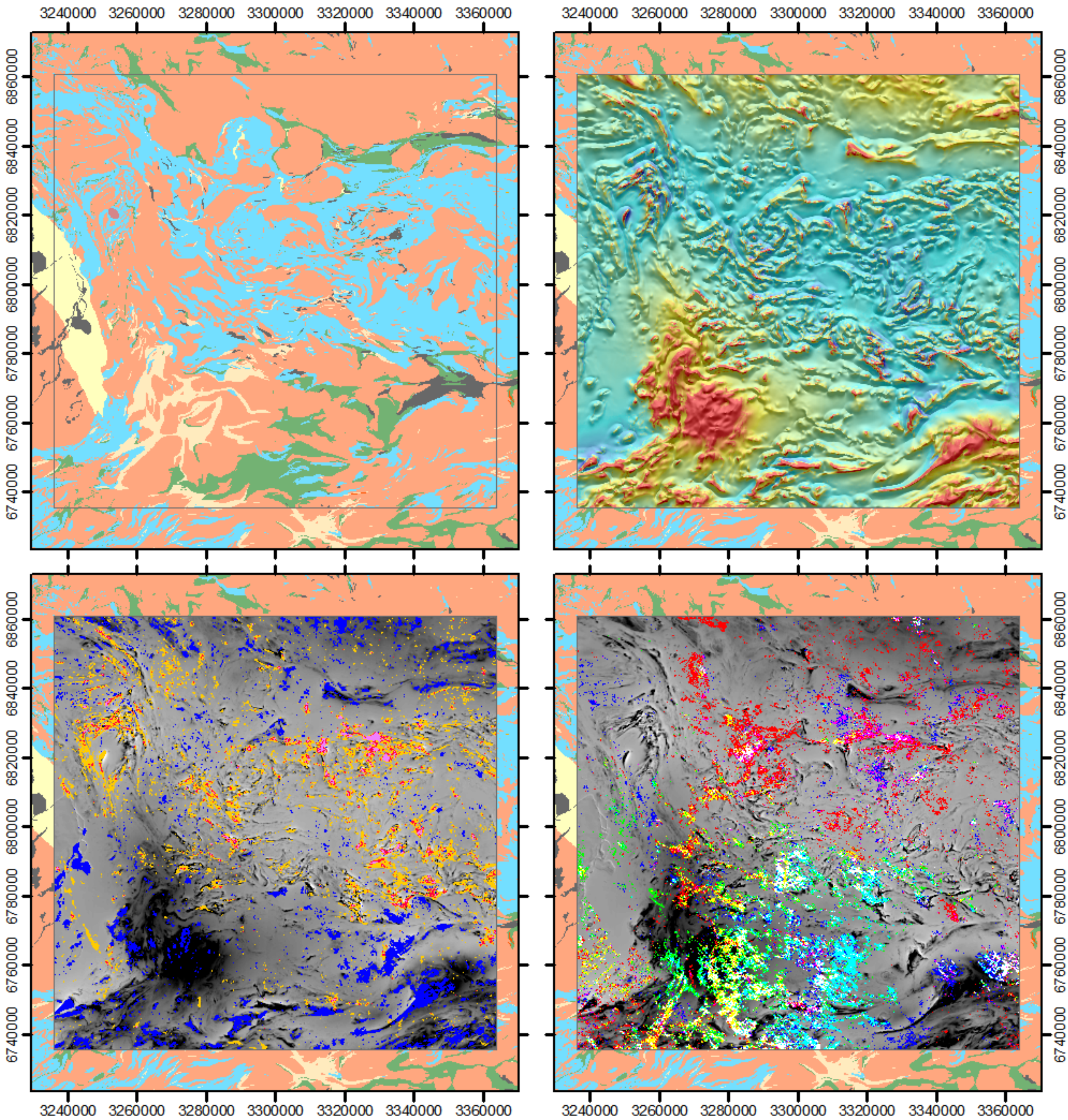


Fig. 7. Geophysical provinces in the Pirkanmaa-Vammala region compared with the digital bedrock map of Finland (from Airo & Leväniemi 2012).
Top left: Lithological units. Brown = granitoids, blue = migmatite belt, green = volcanic rocks.
Top right: Upward-continued magnetic field. The migmatite belt is displayed as a regional magnetic low with local anomalies. The volcanic belt is associated with more regional magnetic anomalies.
Bottom left: Thematic EM map overlying a magnetic grey-scale image. Blue = magnetic susceptibility source (magnetite), typically within the volcanic belts. Yellow to red = increasing conductivity, typically within the migmatite belt.
Bottom right: Ternary image presentation of radiometric maximal cut-offs on top of a magnetic grey-scale image. Red = K, green = Th, blue = U.

4.3 Structural Interpretation: Basic Concepts

Potential field data are the basic geophysical material for structural interpretation. Processed gravity and magnetic fields may uncover or enhance structural features that are not readily observed from total field data. Processed datasets representing different wavelengths used together with other geo-datasets, such as geochemistry or geology, bring valuable information for structural interpretation at both regional and local scales.

The traditional application of magnetic data has been in the detection of faults or lithological contacts by manual identification of lineaments or body outlines. Lithological units are often outlined by coherent magnetic anomaly patterns and a uniform average magnetic anomaly intensity over the whole unit. Lineaments represent structural discontinuities in magnetization, and continuous close-to linear magnetic features may correspond to dykes or non-magnetic features to faults, respectively.

Common techniques for enhancing structural patterns are already briefly described in Section 3.3 of this report. Simple horizontal and vertical derivatives (dx, dy, dz) can be used to derive more advanced spatial derivatives, which are nowadays in common use in structural mapping. During recent decades, new derivative-based transformation methods have been introduced in the literature (Verduzco et al. 2004, Pilkington & Keating 2004). The effect of the various adopted techniques on the magnetic signature over a dipping plate is compared in Figure 8, and an example of 2D lineament analysis based on tilt derivatives is presented in Figure 9.

The dimensions of the structural features to be interpreted outline the resolution of data that is best suited for the anomaly analysis. The mapping of *local-scale*, subtle indications of faults and fractures – or even the magnetic signature of jointing – may require the suppression of long wavelengths (caused by deeper sources) to enhance near-surface structures. The tilt derivative (TDR) is effective in highlighting deformation patterns such as foliation and fracture/jointing trends. Directional filters of magnetic data may be used to emphasize a particular direction or structural trend within a structural province. When searching for *regional*, continent-scale fault or shear zones or boundaries of geophysical provinces, upward continuation of survey data may be needed. Upward continuation may also be applied for the reduction of noise in data or for the separation of deeper magnetic sources from near-surface sources.

Algorithm-based image processing of magnetic data is gaining increasing interest in structural analysis. This processing rapidly produces regional-scale structural interpretations that are objective and repeatable (Core et al. 2014). It can additionally be used to perform a very detailed analysis of geological structures. The data are filtered, for instance by edge-detection methods, to highlight ridges, valleys and edges. These particular filters are independent of the signal amplitude, meaning that subtle or high-amplitude anomalies are given the same weight. Such results provide an overview of the general orientations or trends of structures and of cross-cutting or intersection structures.

Edge detection methods rely on the automatic location of local derivative maxima (or, in some cases, minima). Many spatial derivatives gain their maximum value over a contact (edge). Figure 10 compares two available edge detection methods, i.e. multi-scale edge analysis ('worming', see Section 4.4) and curvature analysis (implemented by the USGS for Oasis Montaj; Phillips et al. 2007). Curvature analysis is a raster analysis method whereby a surface is fitted in a sliding 3 x 3 point set and the surface curvature (shape) is examined. Local maxima may indicate contacts and local minima are related to faults. Depth estimates of the anomaly source can be made using specific techniques (See Section 4.5). For details of and references to different enhancement methods, see Pilkington & Keating (2009). An example of the application of worming in the analysis of local-scale structural patterns is presented in the context of a case study in Section 4.4.

The worming technique to map the positions of gradients in the potential field seeks to establish a continuity of line elements, so as to outline the regional scale features. This is an automated edge detection routine, developed by CSIRO and Fractal Graphics (Hornby et al. 1999, Archibald et al. 1999). It is applied to gravity and aeromagnetic data over multiple (above-ground) height levels of upward continuation from which the positions of the maximum gradient are detected. Visual inspection of the data reveals breaks or truncations and offsets of worm traces. Where a series of truncations appear to define a linear trend, these truncations have been interpreted as cross faults, many of which have no density contrast across them. The interpretation seeks to capture such lines and incorporate them into the digital processing. Evaluation of length dimensions may then help to determine the depth extent, with potential implications for the location of major hydrothermal deposits. Worming is generally used to aid the outlining of structural features, in particular large-scale structural provinces.

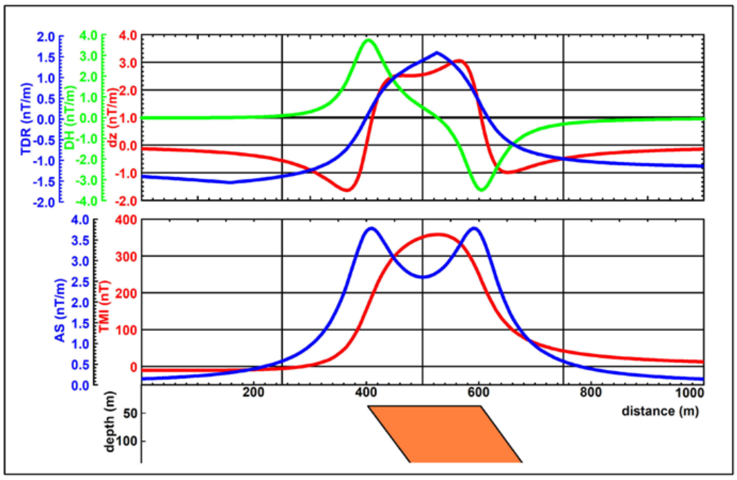


Fig. 8. Anomaly signatures of different structural enhancement methods over a dipping plate.
TMI = Total magnetic intensity, reduced to the north magnetic pole
AS = Analytical signal of TMI
dz = Vertical derivative of TMI
DH = Horizontal derivative of TMI (dxy)
TDR = Tilt angle of the total derivative of TMI

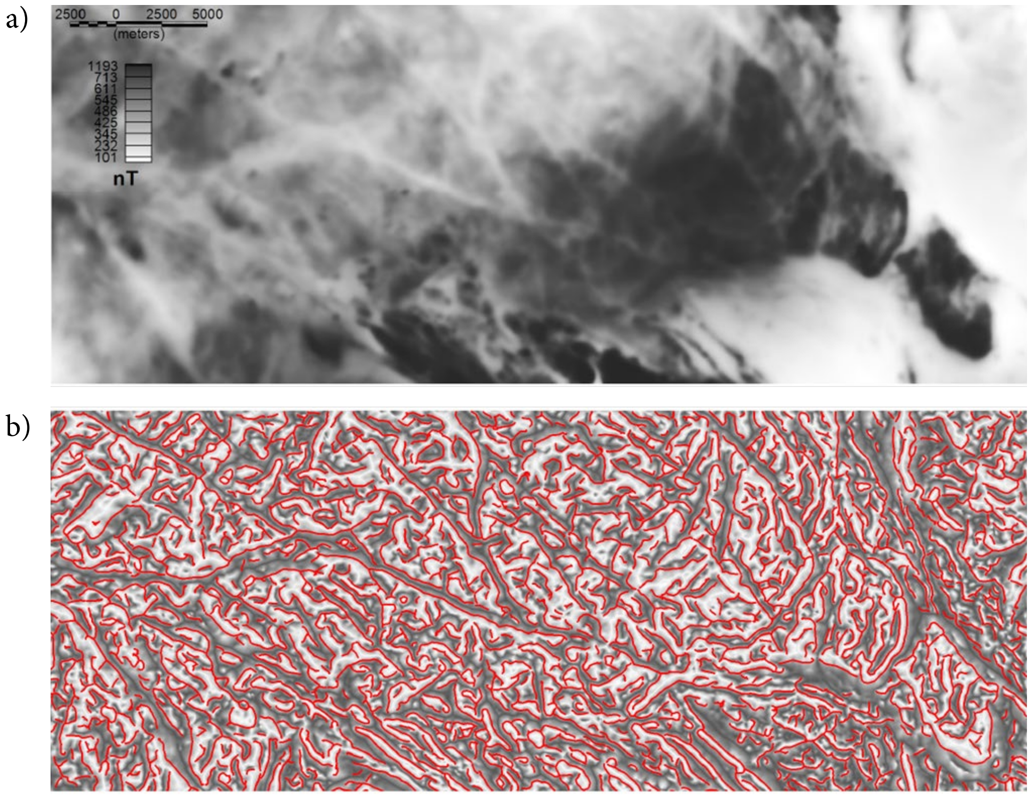


Fig. 9. Tools for 2D lineament analysis: a) magnetic data for visual inspection; b) structural features enhanced by maxima of the total horizontal derivative of TDR (red).

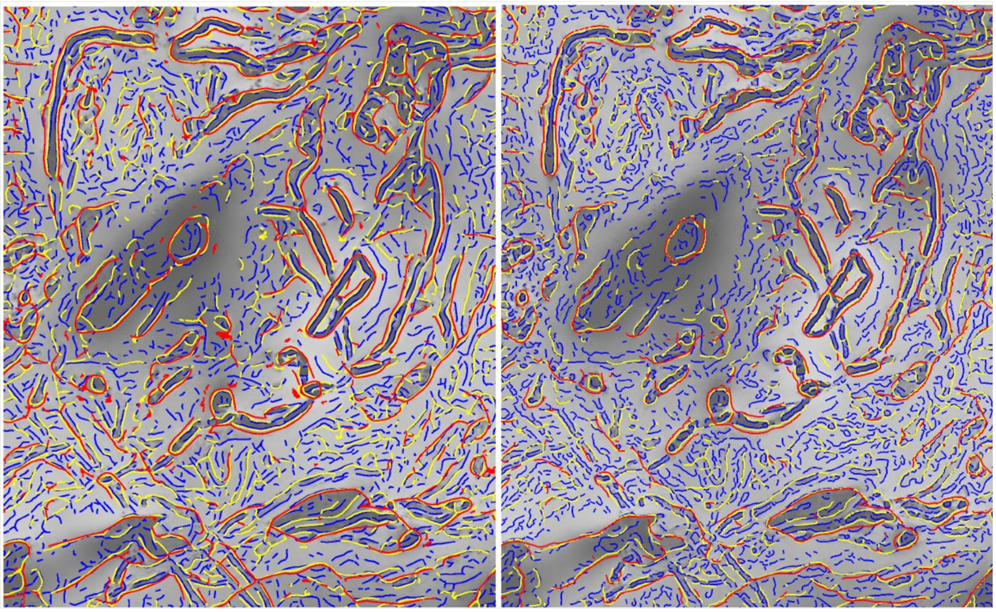
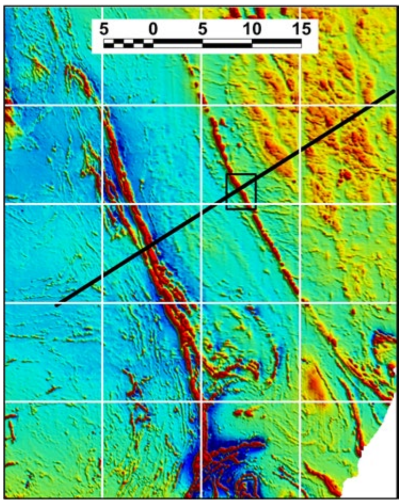


Fig. 10. Worming (left) vs. curvature analysis (right). The map area is 40 km wide. Blue: close to surface; yellow and red: deeper features. (Adopted from Leväniemi 2012.)

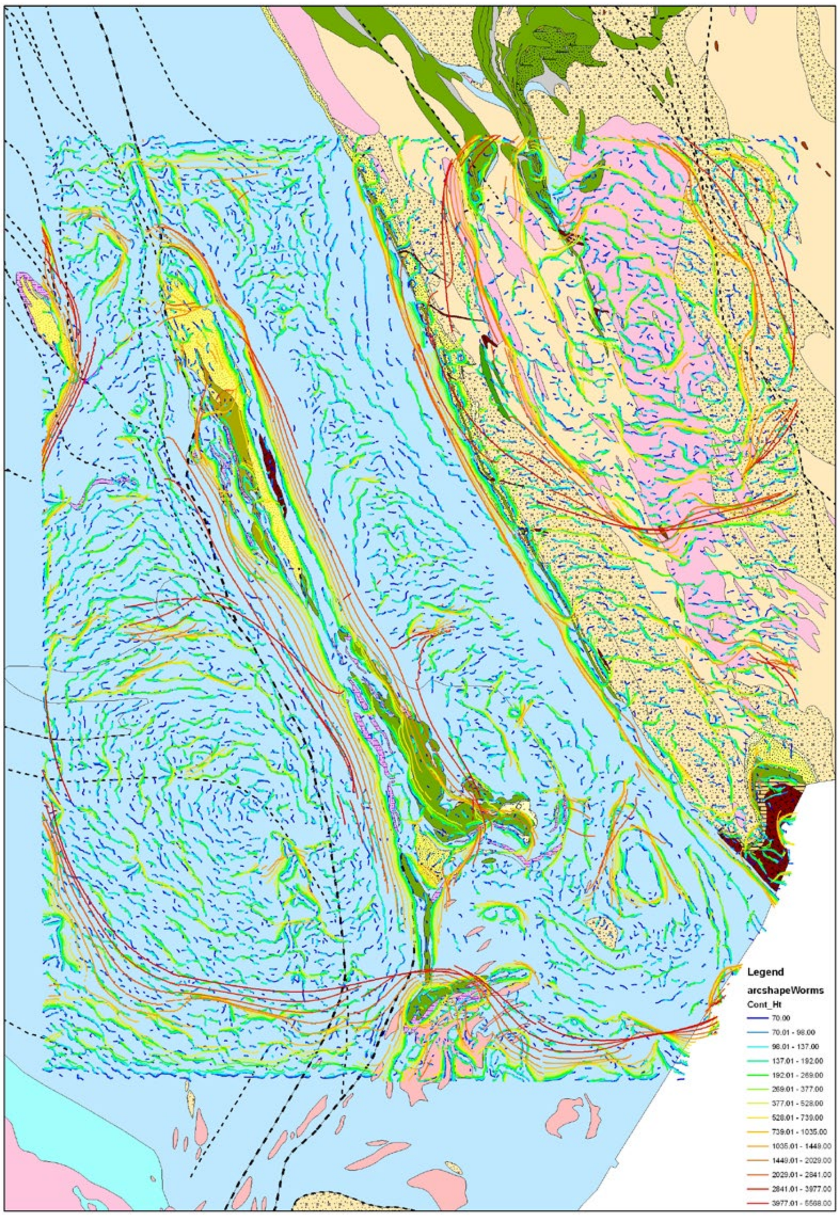
4.4 Case Study: Structural Interpretation with the Depth Aspect

High-resolution airborne magnetic data contain anomalies from low to high frequencies. The anomalies with the highest frequencies are caused by small, near-surface magnetic bodies, whereas the low frequencies arise from wide and deep magnetic sources. The elevation of measurement can be simulated by continuing the measured magnetic data either downwards or upwards. Upward continuation of the measured data can be used to detect the lower wavelength anomalies (structures with a considerable vertical extent) from the total signal. When combined with any structural filters, it is possible to gain valuable information on the relative depths of the magnetic/geological units. Figure 11a presents total magnetic intensity data, including northwesterly-striking magnetic anomaly signatures. The location of a cross-cutting profile used in modelling is indicated. Figure 11b shows the structural interpretation of magnetic source bodies of the area presented in Figure 11a. Simplified TDR derivatives of three upwards-continued TMI datasets (1 km, 2.5 km and 5 km) were used. The quantitative interpretation (Ruotsalainen 2008 and 2013) is performed simultaneously for data continued to five different levels (Figure 11c). Higher levels of upward continuation give more reliability to the interpretation of the deeper parts of the model. Contacts of magnetic formations have been interpreted from GTK's aeromagnetic data (~30 m). Comparison with lithology reveals the connection of each magnetic body with a lithological unit and its relative depth extent. For example, volcanic rocks (green in lithology, western part of the profile) are interpreted to reach quite deep, at least to the depth of 5 km. Similarly, the granitoid area in the east contains anomaly sources reaching the depth of 3 km. Figure 10d is the result of worming of pseudogravity data and enhances the near-surface structure with short, bluish lines. The deeper structures that can be related to the 5 km level in Figure 11b, are indicated by red-yellow, continuous lines.

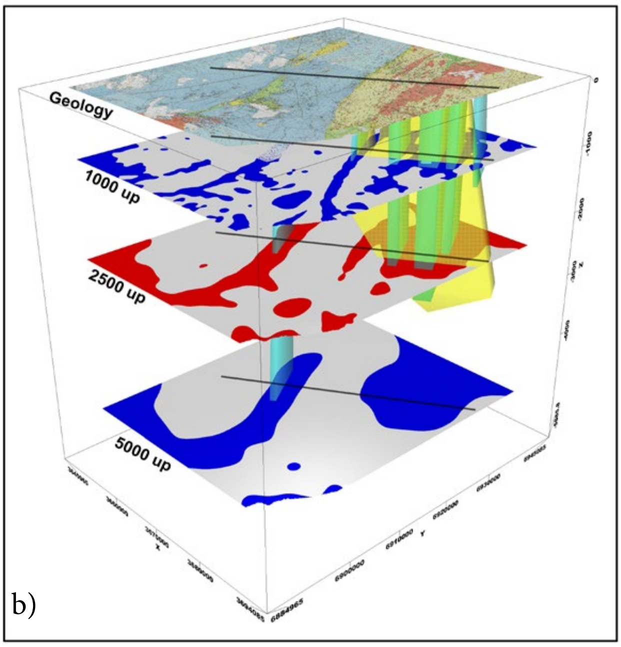


a)

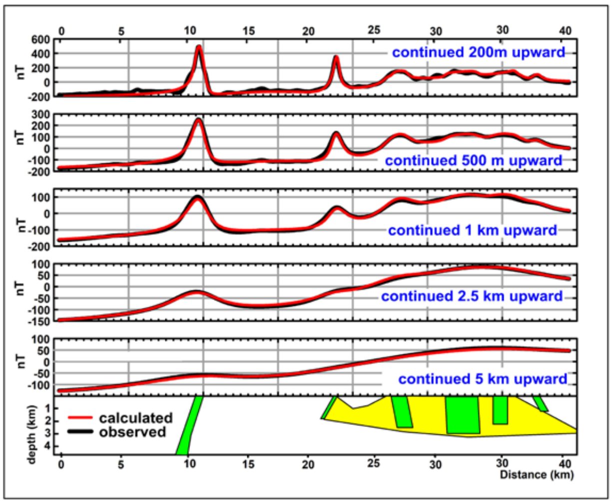
Fig. 11. Structural interpretation, Karjala, eastern Finland.
a) Magnetic total field. The modelled profile (10c) is indicated with a black line and the data used in Fig. 2 are within the black square.
b) Interpretation of magnetic source bodies using classified tilt derivatives of three upward-continued total magnetic intensity datasets (1 km, 2.5 km and 5 km). The profile modelled in 11c is indicated.
c) Modelling of the upward-continued data to the depth of 5 km.
d) Pseudogravity 'worms' indicate structural features.



d)



b)



c)

4.5 Case Study: Depth Interpretation of the Non-magnetic Top Layer

Magnetic airborne data provide a versatile source for interpreting the contacts, dips, magnetization and other features of geological formations, with the condition that the rock type is magnetically anomalous. If the magnetic bodies are overlain by sediments, lavas or other non-magnetic rocks, the measured anomaly may be attenuated. The same applies to a thick overburden. The depth of the non-magnetic layer can be interpreted, for instance, by quantitative modelling. Semi-automatically, the depth to magnetic sources can be estimated using Euler deconvolution or Source Parameter Imaging (SPI™), as applied, for example, by Salem and Ravat (2003) and Thurston and Smith (1997).

Our example is from Tanzania, where detailed airborne geophysical surveys were conducted using GTK's 3-in-1 system at a 200-m line-spacing and a terrain clearance of 40 m (Airo et al. 2007). The so-called Bukoban sediment is a thick sandstone layer overlaying Precambrian basement in southern Tanzania (Fig. 12). There are magnetic rocks below the sandstones, as indicated by longer-wavelength magnetic anomalies. The depth of the sandstone layer was estimated by using quantitative interpretation: Euler deconvolution and SPI™. On the aeromagnetic total magnetic intensity (TMI) map (Fig. 12a), the interpreted outline of the Bukoban sediment is indicated with white dashed lines. Euler deconvolution applied to TMI presumes knowledge or an assumption of the types of magnetic sources (e.g. contact, dyke, sill, sphere). Some other choices of the interpreter may also influence the results, but if applied to the analytical signal (AS), these disadvantages can be overcome, as seen from the depth solution (Fig. 12b). SPI™ utilizes the tilt angle of the total derivative of TMI (TDR) and the horizontal derivative of TDR. The resulting depth estimates of the contacts of magnetic bodies must be classified to find solutions for the formations to be examined (Fig. 12c). Quantitative modelling has been performed from airborne and ground magnetic data across a magnetic dyke, which is overlain by the sediments along the line A–B. To the southeast, at Mtambo, a younger dyke penetrates the sandstone formation. Combining the results of Euler deconvolution, SPI ™ and quantitative modelling, the cross section of sediment cover can be reconstructed (Fig. 12d). The thickness of the Bukoban sediment along profile A–B varies between 100–200 m. The bottom of the sandstone formation gives the topography of the crystallized basement.

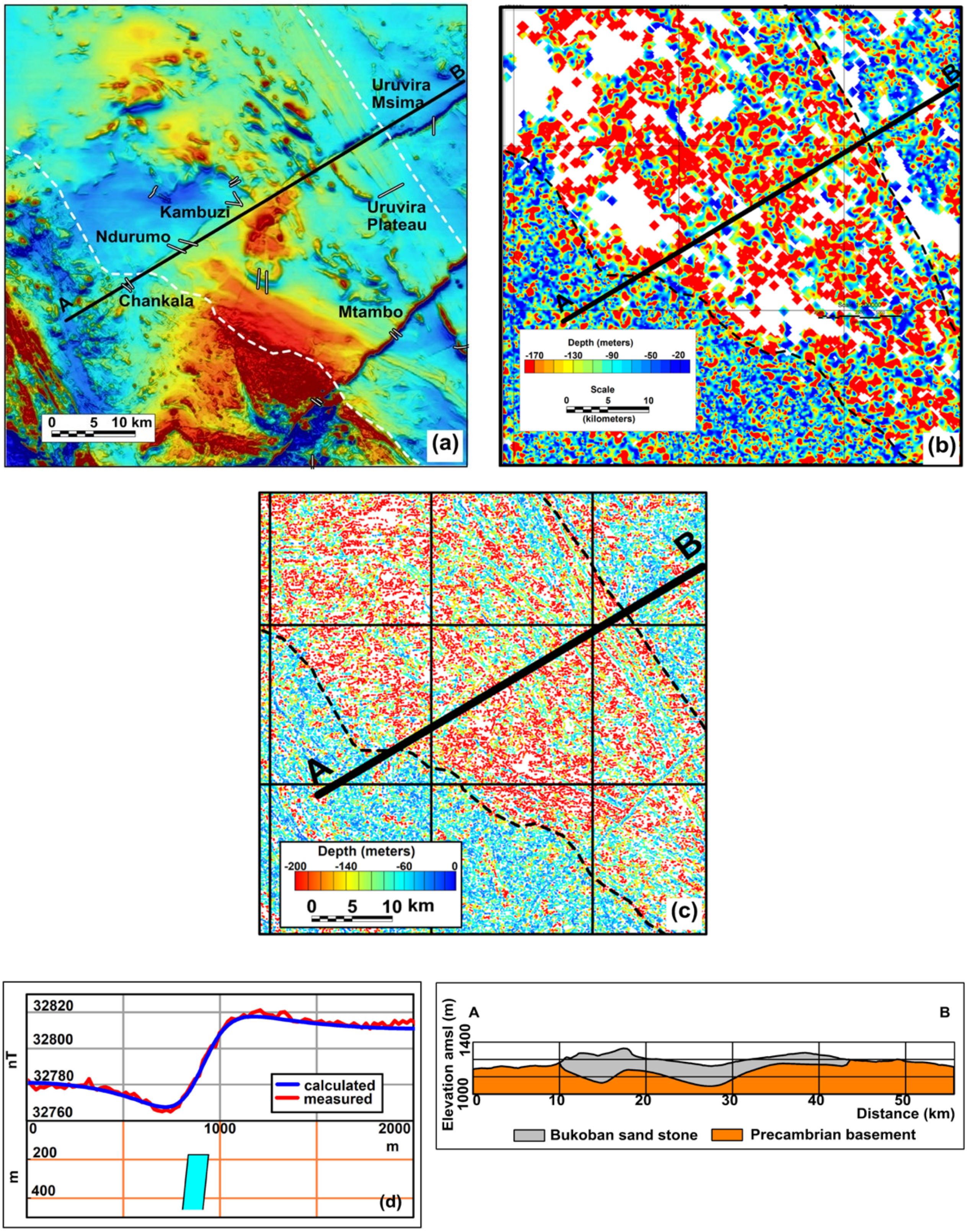


Fig. 12. Depth modelling of Bukoban sediment (courtesy of the Geological Survey of Tanzania).
a) Total magnetic intensity, ground magnetic profiles and outline of the sandstone (white dashed line);
b) Depth to magnetic source from Euler deconvolution;
c) Depth to magnetic source from SPI™;
d) The final model of Bukoban sediment at profile A–B.

5 SOIL MAPPING

5.1 Introduction

The airborne electromagnetic quadrature (out-of-phase, imaginary) component can be used for mapping areas of sediments with a fine grain size and areas with a resistive, thin overburden, or exposed areas. The thickness of quaternary formations can also be interpreted, especially from multi-frequency measurements under favourable conditions.

Airborne radiometric measurements register the earth's natural gamma-ray radiation reaching a depth of less than 1 m. Radioactive isotopes are present in all soils and they are primarily related to the mineralogy and geochemistry of the parent material, and secondarily to weathering processes that lead to soil formation. In glaciated terrains, as in Finland, glacial processes have also contributed to the concentration of radioactive elements in soil.

Investigation of the distribution of various soils or weathering products is aided through the integrated use of airborne magnetic, electromagnetic and radiometric data, complemented with satellite imagery. Ratios of airborne radiometric potassium (K) and thorium (Th) channels and the ternary images of potassium, thorium and uranium (U) are useful in highlighting the radiometric signatures of various weathering products. Electromagnetic data are effective for mapping electrically conductive overburden. Magnetic and digital elevation data (DEM) enhance the structural patterns and soil textures. Through weathering, uranium and thorium can be adsorbed by clays or co-precipitated with iron oxides. Uranium and thorium are concentrated in the resistant secondary minerals monazite and zircon. The chemical breakdown of mica and feldspar minerals results in reduced K concentrations. Weathered felsic rocks usually show reduced U and Th, whereas weathered mafic rocks exhibit elevated concentrations of U and Th.

5.2 Case Study: Mapping Soil Properties using Electromagnetic and Radiometric Data

Potassium has successfully been used to identify stratified sand and gravel formations and coarse-textured till (Hyvönen et al. 2005), whereas thorium and especially the K/Th ratio are considered to be the most characteristic indicators of the soil's clay and silt concentrations (Väänänen et al. 2010).

An example of the use of airborne radiometric and electromagnetic data in mapping soil properties is presented in Figure 13. The electromagnetic quadrature component together with potassium radiation and the ratio of potassium to thorium (K/Th) were used to locate bedrock terrains with a thin resistive overburden (Väänänen et al. 2010). The interpretation was checked using a digital terrain model and bedrock observations. The distribution of K/Th ratios is presented in Figure 13a. This ratio was used to distinguish coarse- and fine-grained soils: in Figure 13b, the high K/Th ratios indicate coarse-grained sediments. The attenuation of gamma radiation by soil moisture provides the potential for indirect estimation of the soil material based on its fine-fraction content. The volumetric water content of soil varies spatially due to its physical properties. The parent soil materials in Finland have been derived from a diversity of lithologies and their physical properties tend to have high spatial variability. Dry soils with a coarser texture show higher gamma radiation values. In Figure 13c, the low-K areas were classified to indicate the coarse variation in peat thickness (brown background). The fine-grained soil deposits can also be mapped according to the increased response of the electromagnetic quadrature component (Fig. 13d).

Another example is the extraction and scaling of low values of the quadrature component (Fig. 14). Areas of exposed bedrock or thin Quaternary cover can be mapped in non-conductive bedrock areas.

The application of gamma-ray surveys in peat research is based on the attenuation of gamma radiation by water. Theoretically, it has been calculated that the high water content in peat (90%) will totally absorb gamma rays if the thickness of the peat exceeds 60–70 cm. Based on this, mire areas can be classified as either shallow or deep (Fig. 15). The best results have been achieved by using the gamma-ray flux from potassium (Virtanen & Vironmäki 1985).

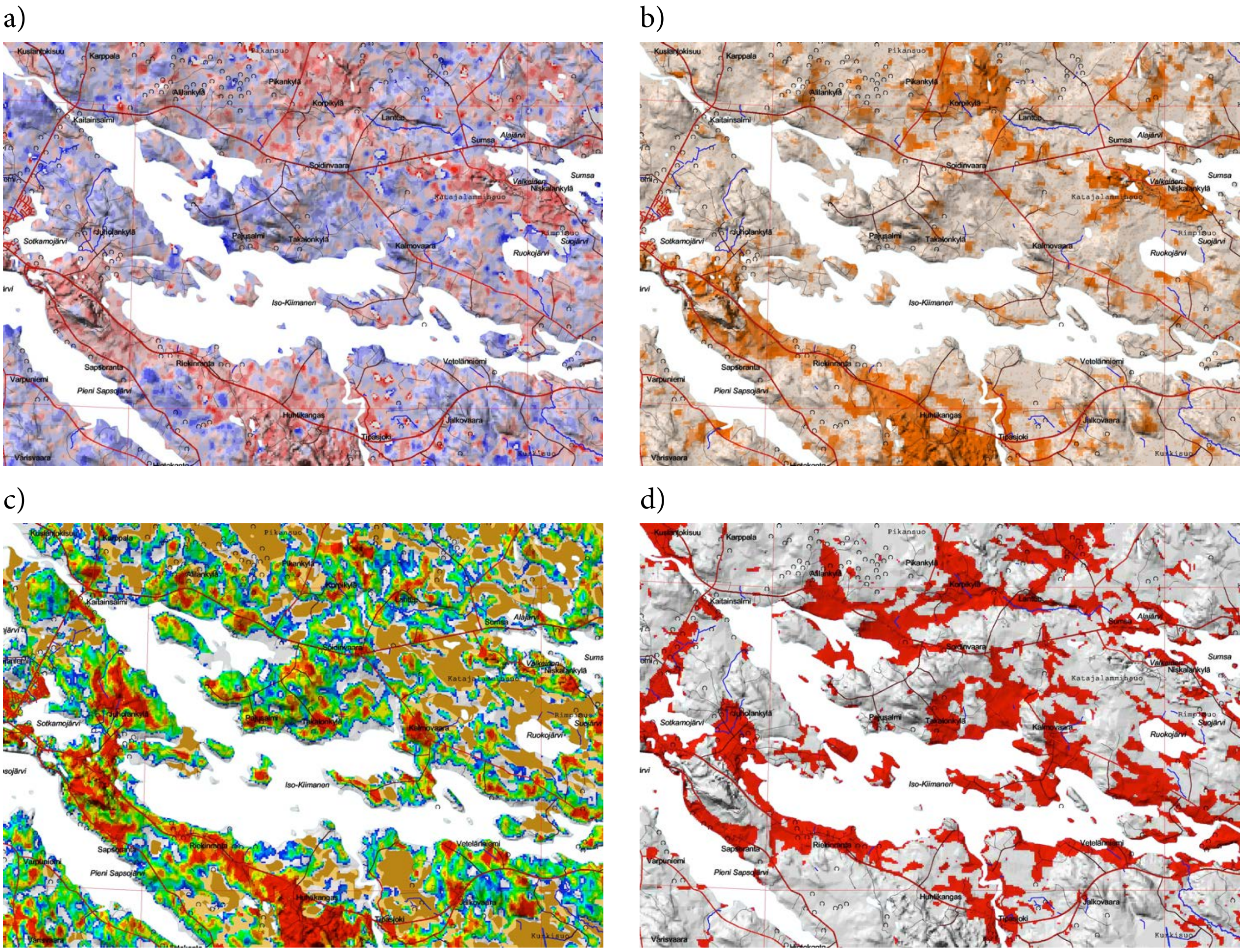


Fig. 13. Mapping soil properties using airborne radiometric and electromagnetic data. The digital elevation model presented is as background. Contains data from the National Land Survey of Finland Topographic Database 03/2013.
a) (Un)classified K/Th ratio. Blue = low values, red = high values.
b) Coarse- and fine-grained sediments distinguished using the K/Th ratio. Brownish areas have a high K/Th ratio, which indicates coarse-grained soils.
c) Mapping wetlands and the thickness of peat using potassium (K). Brown areas: low potassium radiation due to thick peat. Light brown areas indicate shallow peat.
d) Fine-grained soil deposits inferred from the electromagnetic quadrature component. Red = high values denoting fine-grained soils.

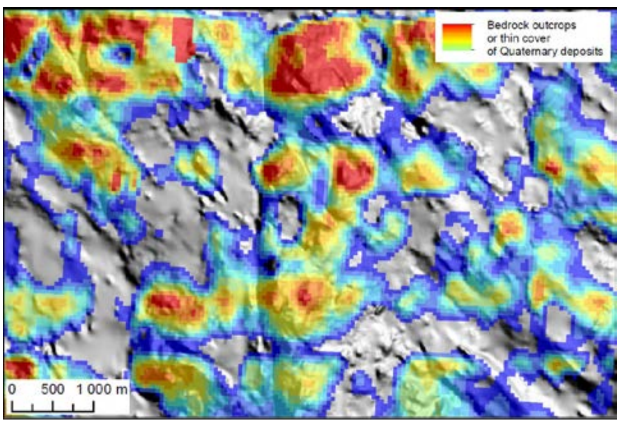


Fig. 14. Mapping of the exposed bedrock and/or thin cover of Quaternary deposits using the electromagnetic real (out-of-phase) component. The background is the digital elevation model.

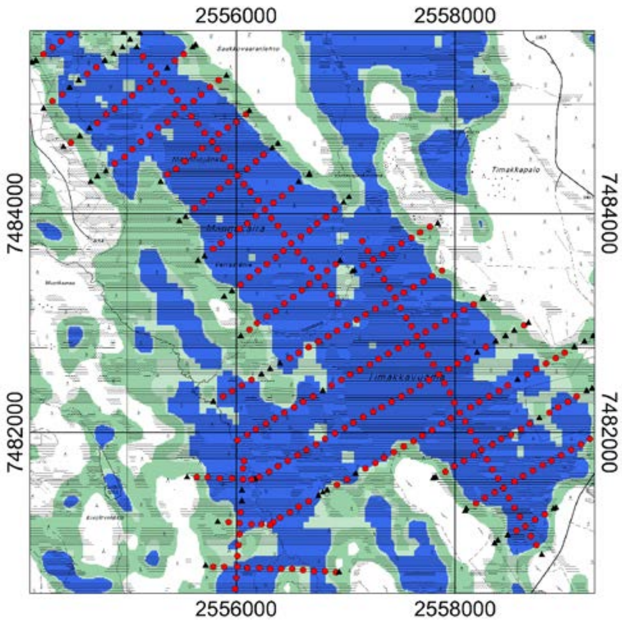


Fig. 15. Peat research in Timakkavuoma. The gamma radiation data in the K-channel were scaled so that areas with a thick layer of peat are coloured blue and areas with a shallow layer of peat are green. Depth measurements, based on ground surveys, are indicated as a black triangles when a peat layer is below 0.6 m and as red circles when it is above 0.6 m (from Hyvönen et al. 2005). Contains data from the National Land Survey of Finland Topographic Database 03/2013.

5.3 Case Study: Peat Layer Thickness Estimations using Electromagnetic Data

The thickness of the peat layer was interpreted from aerogeophysical data using the 1D layer inversion program Airbeo developed by AMIRA project P223F (Raiche 2008). The P223 software is suited to the planning and interpretation of electromagnetic surveys. At several peatland locations, the average resistivity values of the peat and possible 'gyttja' layers were measured *in situ* and used for interpretation. The 1D layer model, regardless of its generalization and simplicity, gives reasonable results when the interpreted structure is large enough in relation to its depth (Fig. 16a). For peatlands (depth typically less than 5 m), this means a horizontal extent of 100 to 300 m. Around the peatland margins and near the upland forest sites within the peatlands, the model is relatively poor and the results are erroneous. In 1D layer modelling, it is common to use the so-called electrical footprint. This is the area in which the induction currents are concentrated in the ground below the measuring unit of the aircraft.

An in-house-developed novel inversion-based method for modelling peat depths was described in Laatikainen et al. (2011). The method enables the use of all available peat-depth data, drilling data and mire outlines, aerogeophysical data and ground penetrating radar (GPR) measurements. The method is based on both mathematical and geological facts and it has been tested on 13 mires with variable geological structures and datasets. For example, Soidinsuo in Central Finland (Fig. 16), with an area of 124 ha, was studied through 20 investigation sites and 39 depth drillings and modelled using airborne electromagnetic data. Different data sources can be combined in various ways and with a small amount of effort to obtain a depth model for a peatland. The method makes the sampling of depth data more effective, as a preliminary model at each stage of data sampling can be provided. The characteristic uncertainties of each data type are also taken into account in the depth model itself.

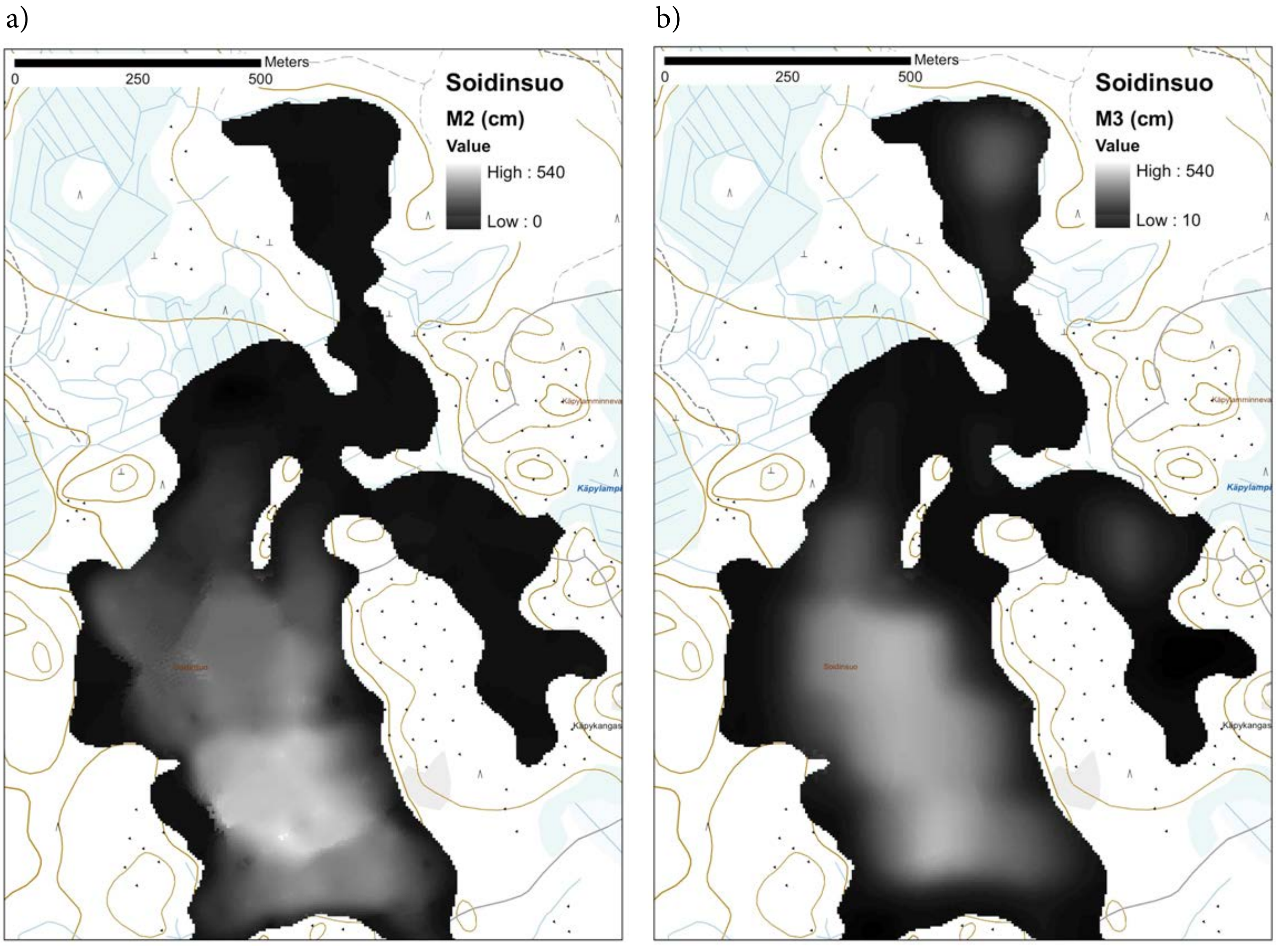


Fig. 16. Interpretation of soil depth using two methods: a) electromagnetic interpretation (Amira, 1D layer inversion); and b) ground penetrating radar (GPR) and drilling data. Contains data from the National Land Survey of Finland Topographic Database 03/2013.

6 MINERAL POTENTIAL

6.1 Introduction

The physical properties of ore deposits are the link between mineralogy and geophysical responses. Most metallic minerals are attributed with specific geophysical properties that can be determined by petrophysical laboratory measurements. Geophysical parameters provide the key for mapping the signatures of different mineralization styles and support the recognition of similar signatures elsewhere (see Section 6.3).

Airborne geophysical databases provide an enormous amount of source data that can be used for

- direct/indirect identification of mineral deposits/potential targets,
- analysis of the key parameters describing ore forming processes or alteration zones,
- interpreting the structural control and its relationship with the large structure,
- assessment of mineral prospectivity by using geophysical data.

6.2 Interpretation for Mineral Potential: Basic Concepts

Geophysical interpretation for mineral potential and exploration purposes is facilitated with multivariate airborne geophysical datasets that can be used in an integrated manner. The detection of target mineralization or any signature related to geological processes associated with mineralization largely depends on the data resolution and quality. Very strong indications of mineralization are sometimes sought, and reduced, subtle features or indirect evidence such as structural control at other times. A more detailed summary of the key geophysical parameters for different mineralization styles is currently under preparation at GTK (Airo M.-L. (ed.) in prep.). For minerals, or other raw-material exploration, the following approach may improve the investigation:

Metallic ore minerals and their geophysical properties:

- Gold deposits
  - Geophysical properties depend on the associated minerals
- Sulphides, good electrical conductivity
  - Pyrite and chalcopyrite are non-magnetic
  - Pyrrhotite, the monoclinic type is ferrimagnetic
- Oxides, magnetization
  - Magnetite or titanomagnetites are associated with intense magnetization
  - Chromite, may be associated with magnetite

Chemical alteration associated with mineralization:

- Reduced magnetization
  - Hydrothermal alteration processes commonly destroy magnetite.
  - Disturbed magnetic anomaly pattern with destruction of magnetite grains.
- Increased magnetization
  - Increased susceptibility if there has been production of coarse-grained magnetite.
  - Increased intensity of remanent magnetization if there was production of fine-grained magnetite or monoclinic pyrrhotite.
  - Detailed studies of remanent magnetization for the dating of magnetic minerals.
  - An enhanced magnetic anomaly intensity is generally related to the production of new magnetic material.
- Increased conductivity
  - Sulphidization: the concentration of sulphides is increased.
- Changes in radiometric data
  - Th is typically immobile in mineralization processes or it can only partly be depleted in areas of intense K-alteration and silicification. The K/Th ratio gives a better indication of hydrothermal alteration than any single radioelement alone.
  - Th shows a higher-grade enrichment in advanced differentiation than U, and Th/U ratios are therefore useful when examining the degree of differentiation within igneous suites.
  - A high U/Th ratio in granite reflects differences in oxidation states during the late-stage processes, and U-enriched granites may consequently indicate a source area where polymetallic U deposits have been formed in later processes.
  - Potassium is commonly added to host rocks by mineralizing hydrothermal fluids; hence, the K-channel has been shown to be the most reliable pathfinder in locating hydrothermal ore deposits, especially gold deposits.
  - In many gold deposits, Th has been mobilized and depleted with a simultaneous increase in the K-channel, although Th is generally unaffected by alteration processes.
  - Uranium is a very mobile element in hydrothermal and other geological processes. Consequently, erratic U anomalies along with or without an increase in K-channel counts are always interesting, and may indicate a U-bearing mineralized system. However, U can also decrease in hydrothermal processes, or it can be removed earlier from the solution. Therefore, the K/U ratio is not always a good indicator in identifying mineralizations.

Structural control, regional or target scale:

- Mineralization associated with block boundaries or regional faults
  - Analysis of structural provinces and lineaments using regional potential field data
- Mineralization associated with local-scale structures such as brecciating or fracturing
  - Detailed study of aeromagnetic high-resolution data
- Analysis of structures may benefit the timing of mineralization
  - Detailed determinations of remanent magnetization or the anisotropy of magnetic susceptibility (AMS) for dating magnetic minerals.

Mineralization-related geophysical signatures may be either very strong or subtle, or they may cover or disturb each other. Searching for anomalous signatures possibly related to a certain mineralization type may be accelerated by the integration of multivariate geoscientific datasets in interpretation. Using appropriate processing of airborne geophysical data gives a more profound understanding of the key geophysical parameters to identify interesting targets. A systematic approach using spatial analysis techniques such as principal component analysis or unsupervised classification often reveals information that is not readily evident using conventional procedures.

6.3 Case Study: Identifying IOCG Potential Areas with Airborne Datasets

Petrophysical analysis of samples from known IOCG formations in Finland (Fig. 17) demonstrated that most of the studied samples are highly magnetic and carry remanence that is due to their magnetite and/or monoclinic pyrrhotite. The magnetite-bearing samples have high magnetic susceptibility of the order of 1–10 (SI units) and their Q-ratios (ratio of the remanent to the induced magnetization) are generally low, below 1–2. Q-ratios grow with a decrease in the magnetite grain size in the samples, meaning that the role of remanent magnetization becomes more significant. Q-ratios are then of the order of 1–50, which is also generally typical of any rocks containing significant amounts of monoclinic pyrrhotite. The highest Q-ratios in Figure 17 are attributed to IOCG samples that contain either fine-grained magnetite or/and monoclinic pyrrhotite as their prevalent magnetic mineral. Such high Q-ratios, due to the intensive remanence, affect the magnetic anomaly patterns in a typical way (Airo 2005).

Based on petrophysical analysis, a subset of the national aerogeophysical data for an area with known showings was processed into thematic magnetic and electromagnetic maps presenting anomalies with intense variation in magnetization and shape. Such features are often related to IOCG ores (Fig. 18). Magnetic data analysis locates horizons with intense magnetic variations, whereas electromagnetic data classification differentiates between magnetite sources (negative Re/Im ratio values because of high susceptibility) and pyrrhotite sources (moderate to high ratio values because of electrical conductivity). Comparison with known deposits shows that these thematic maps together with structural analysis can be used in identifying targets with a high concentration of magnetite, such as the occurrence of IOCG.

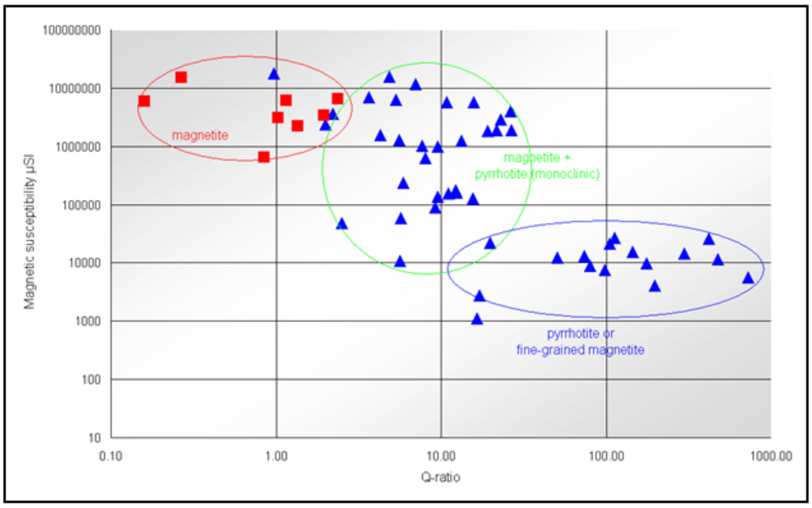


Fig. 17. Magnetic properties for IOCG samples from northern Finland. Three sub-categories based on varying magnetic mineralogy: 1) lowest Q-ratios, coarse-grained magnetite (red squares); 2) Q-ratios ~10, magnetite + ferrimagnetic pyrrhotite (blue triangles); 3) Q-ratios >10, fine-grained magnetite + pyrrhotite (blue triangles).

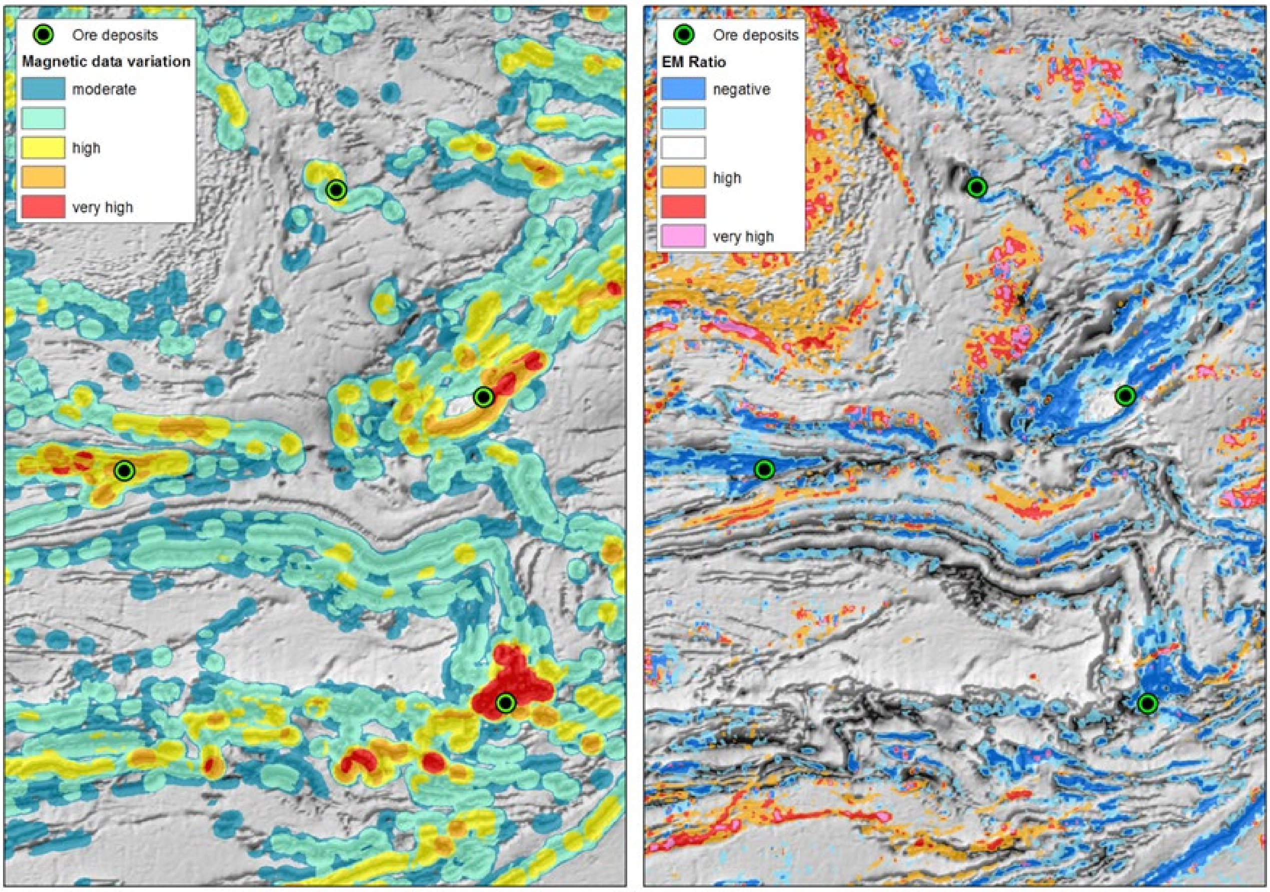


Fig. 18. Thematic aerogeophysical maps with possible IOCG occurrences in the Perä-Pohja schist belt, northern Finland. The map area is 35 km wide. Left: Local value range analysis of magnetic total field data. Right: EM ratio (in-phase/quadrature or 'Re/Im'). Negative values denote high magnetic susceptibility and low electrical conductivity, while high values denote high conductivity.

6.4 Case Study: Prospectivity Analysis by using High Resolution Aerogeophysical Data

INTEGRATED INTERPRETATION

Characteristic geophysical provinces were obtained by using a cut-off technique so that different geophysical units could easily be distinguished. Our example is from Kosovo, where airborne geophysical surveys were conducted that covered the whole country using GTK's 3-in-1 method. The nominal flight altitude was 30 m and the line spacing was 200 m. These data formed the basis for the Geophysical Interpretation and Prospectivity Maps (scale 1:200 000) prepared in 2007. In the study area, nine of the most significant classes were highlighted with different colours (Fig. 19). These are based on radioelement contents, electrical conductivity, and the intensity and/or susceptibility effect of magnetic anomalies. The magnetic anomalies caused by magnetite are easily detected on the basis of electromagnetic data. The geophysical structure was described by magnetic tilt derivative TDR, which reveals internal structures.

Geophysical responses to ferrous metal and non-ferrous metal deposits were investigated to obtain the best-correlated data sets for training purposes (Table 1). Of the magnetic data sets, the best correlation was achieved by using the analytical signal (different types of magnetic bodies) and TDR (structural information). The best correlation for electromagnetic data was obtained by using the electromagnetic Re/Im ratio for the frequencies 0.9 kHz and 3 kHz. All radiometric channels, i.e. potassium (K), thorium (Th) and uranium (U), appeared to be of importance.

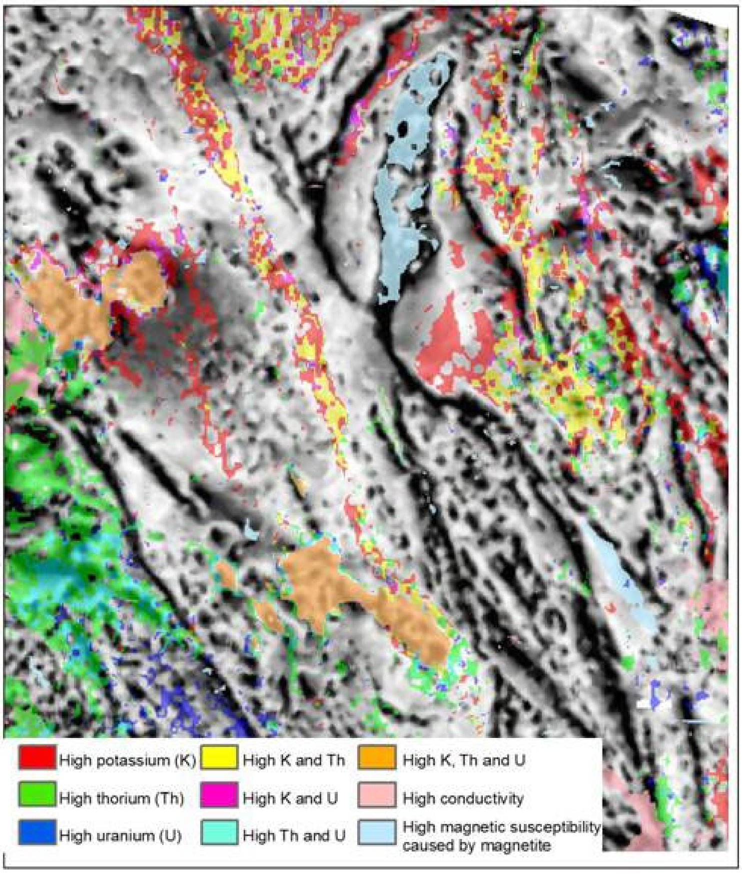


Fig. 19. The result of multivariate analysis of all the aerogeophysical data. The background layer is a grey-scale TDR image (courtesy of ICMM, Kosovo). The map area is 20 km wide.

Table 1. Median values of the dominant geophysical components for ferrous and non-ferrous metal deposits.

	Ferrous metal deposits	Non-ferrous metal deposits
Analytical signal [nT/m]	0.794	0.253
TDR [rad]	-0.343	-0.431
REIM ratio frequency 3 kHz [ppm]	0.529	0.458
REIM ratio frequency 0.9 kHz [ppm]	0.399	0.370
K [%]	0.882	2.129
Th [ppm]	1.392	2.498
U [ppm]	0.777	1.617

PROSPECTIVITY ANALYSIS

Prospectivity analysis was based on the statistical relationship between the occurrences of different commodities, as indicated on the mineral map, and the geophysical response with the mineral deposits and its immediate host rock. The modelling was carried out using Spatial Data Modeller (ArcSDM) for ArcGis 9.2 (Sawatzky et al. 2009) with a supervised neural network approach: Radial Basis Functional Link Net (RBFLN). The training was based on a combination of 'deposit' and 'non-deposit' datasets, which makes the training rapid and more accurate.

The extensive mineral deposit database was available and the most notable deposit types were modelled separately. All datasets were divided into two groups, training and testing datasets, so that training efficiency could be tested. Accuracy assessment was based on the Receiver Operator Curve (ROC) method (Table 2). A narrow range between the lower and upper bounds of the confidence interval, such as in the case of Ni, indicates better results than a wide range, such as for Au. Test data sets were not used in training.

Prospectivity analysis (Fig. 20) revealed that the best geophysical context was obtained for Ni deposits, although the number of validation points was only 3 (Table 3) in comparison with training points (8). The reason for the good results was that the Ni occurrences used in validation were highly representative. The poor accuracy for Au deposits was probably a consequence of an insufficient number of training points, and Au was thus not well investigated in the study area.

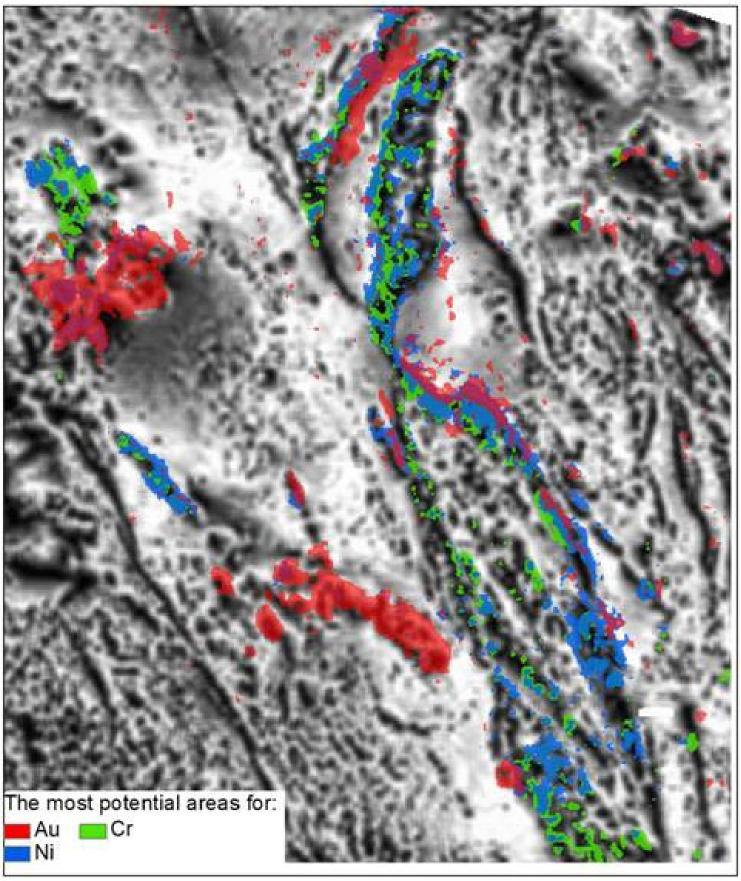


Fig. 20. Integrated prospectivity map of gold, nickel and chrome (courtesy of ICMM, Kosovo). The map area is 20 km wide.

Table 2. Accuracy of modelling. The column "Area" presents probability values describing how well the classification has succeeded. The optimal value is "1" and values below 0.5 indicate failure in classification.

Deposit type	Area	Std. Error	Asymptotic Sig	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
Cr	0.8333	0.0840	0.0156	0.6688	0.9979
Au	0.6667	0.2722	0.4386	0.1332	1.2001
Ni	0.9333	0.0770	0.0280	0.7825	1.0842

Table 3. Number of training and validation points for different deposit types.

Deposit	Training	Validation
Au	5	3
Fe	12	12
Cu	10	6
Cr	20	19
Ni	8	3
Pb-Zn	10	8

7 SUMMARY

This report serves as a user guide for the effective use of GTK's airborne geophysical data. It offers a brief review of tools, methods and techniques that can be easily adopted and routinely applied in extracting geological information from these data. Most of the techniques introduced here are available from geophysical software and in common use. New techniques for processing and transforming geophysical data are continuously being introduced and published. A recent tendency in structural analysis is algorithm-based image processing, which is rapid and free of human evaluation of geophysical datasets. Another long-standing tendency is the use of different geo-datasets in an integrated manner. The algorithm-based approach produces regional datasets that can be used together with the results of manual interpretation and with other geo-datasets such as geochemistry or geology. The acquisition of petrophysical information on the source rocks of geophysical anomalies also has recently gained greater interest as petrophysical databases are becoming available.

GTK's airborne geophysical datasets are extraordinary in many ways and they offer certain specialties for interpretation that are worth noting. Various types of whole-country overview are possible due to the systematic manner in which surveys were carried out. One of the increasing applications is data mining and regional estimations of the ore potential, which requires high-precision processed geophysical data for multidisciplinary analysis. The frequency-domain electromagnetic system was developed for fixed-wing aircraft, and its wide coil separation results in a large footprint of electromagnetic recording. This unique method has many advantages for bedrock or soil applications. For example, one of the most often used applications is the identification of high-susceptibility targets, i.e. the distinguishing of magnetite- or pyrrhotite-bearing rock units. Electromagnetic data integrated with high-resolution magnetic data are excellent for geological mapping and can be used to investigate internal variation in mineralogy or structure in many rock or ore deposit types. The radiometric surveys benefitted from the large size of crystals emplaced in the cabin of the aircraft. The combined interpretation of electromagnetic and radiometric data is widely used in soil investigations, e.g. the classification of soil materials or estimates of soil thickness. Although radiometric data are heavily influenced by Quaternary soils in Finland, they may occasionally be effective and complementary in characterizing rock types or signatures of chemical alteration and the identification of mineralized systems.

Techniques for geophysical interpretation are under rapid development. It is impossible to present an all-inclusive description of the methods, but even these tips and tools may aid in the extraction of geological information from these datasets – hopefully in an eye-opening way.

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Airborne geophysical surveys include high-resolution magnetic, multi-frequency electromagnetic and radiometric datasets and cover the whole of Finland. This remarkable, renewable data storage incorporates source data for a variety of applications, analysis and interpretation. Background information and methodology - 'tips and tools' - for the efficient use of these datasets have been collected into this short 'user guide' to promote and customize practical geological interpretation. We introduce basic concepts for bedrock and soil mapping, and also case studies introducing integrated interpretation and prospectivity analysis for ore potential purposes.

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