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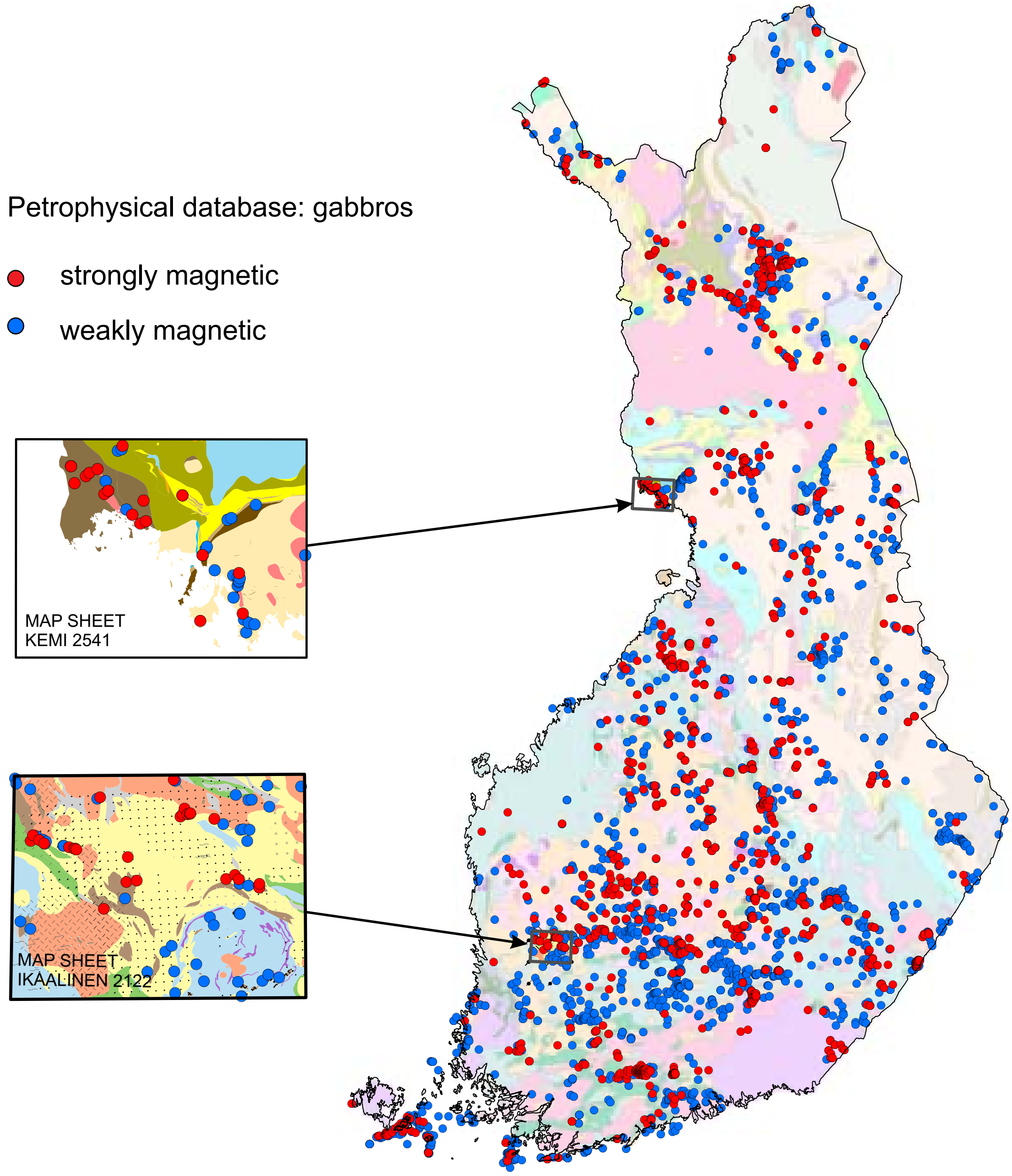

Petrophysical characteristics of Finnish bedrock

Concise handbook on the physical parameters of bedrock

Meri-Liisa Airo and Heikki Säävuori

GEOLOGIAN TUTKIMUSKESKUS **GEOLOGICAL SURVEY OF FINLAND**

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Front cover: Distribution of weakly magnetic ("paramagnetic", blue dots) and strongly magnetic ("ferrimagnetic", red dots) gabbros in Finland based on magnetic susceptibility (k). The susceptibility cut-off between para- and ferrimagnetic categories here is k = 0.002 (SI) (see explanation in text).

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Measurements of the petrophysical parameters of rock and soil samples, such as density, porosity and magnetic and electrical properties, are routinely carried out in the petrophysical laboratories of the three regional offices of the Geological Survey of Finland (GTK): in Espoo, Kuopio and Rovaniemi. The original purpose of initiating petrophysical measurements at GTK was to collect information on density and magnetic properties for the most common rock types in Finland and to create a petrophysical register that covers the whole country. At the end of 1990s, the number of samples measured exceeded 130 000. Based on this extensive collection, different rock types can be petrophysically characterized due to their typical densities and magnetic properties. It may also be possible to distinguish the effect of chemical alteration through the altered physical parameters of rocks compared with their typical values. This report presents summaries on the density and magnetic properties of Finnish bedrock and also serves as a concise user guide to the application of petrophysical data. The results can be used in geophysical interpretations and mapping, in different geological applications and in the evaluation of ore potential.

Keywords (GeoRef Thesaurus, AGI): bedrock, rocks, petrophysics, density, magnetic properties, Finland

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Kivi- ja maaperänäytteiden tiheys- ja huokoisuusmittauksia sekä magneettisten ja sähköisten ominaisuuksien määrityksiä tehdään rutiininomaisesti Geologian tutkimuskeskuksen (GTK) kolmessa petrofysiikan laboratoriossa Espoossa, Kuopiossa ja Rovaniemellä. Petrofysikaaliset mittaukset aloitettiin GTK:ssa alun perin siksi, että saataisiin tietoa eri kivilajien tiheys- ja magneettisista ominaisuuksista. Tavoitteena oli koota koko maan kattava petrofysiikan rekisteri. 1990-luvun lopulla mitattujen näytteiden määrä ylitti 130 000 rajan. Tähän valtavaan näyteaineistoon pohjautuen voidaan eri kivilajeja luonnehtia niille tyypillisen tiheyden ja magneettisten ominaisuuksien perusteella. Keskimääräisestä arvosta poikkeavat fysikaaliset ominaisuudet kertovat kiven mineralogian vaihtelusta tai kemiallisen muuttumisen vaikutuksesta. Tässä raportissa esitetään yhteenvetoja eri kivilajien tiheyksistä ja magneettisista ominaisuuksista ja raportti toimii myös lyhyenä oppaana petrofysikaalisten aineistojen käyttäjille. Tuloksia käytetään mm. geofysikaalisissa tulkinnoissa, raaka-ainevarojen kartoituksessa ja arvioinnissa sekä erilaisissa geologisissa sovelluksissa.

Asiasanat (Geosanasto, GTK): kallioperä, kivilajit, petrofysiikka, tiheys, magneettiset ominaisuudet, Suomi

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CONTENTS

1 INTRODUCTION

The Geological Survey of Finland (GTK) provides country-wide petrophysical data comprising information on the petrophysical parameters of different rock types in Finland. Rock samples have been collected from all over the country with the purpose of covering all the common rock types of the Precambrian crust in Finland. Density, magnetic susceptibility and the intensity of remanent magnetization have been measured at GTK laboratories. The number of determinations exceeded 130 000 samples by the end of the 1990s. This collection of measurements is currently available as an ArcGIS data layer interface. It provides extensive material for regional summaries and rock type characterization, local investigations, and for the modelling of magnetic and gravity data.

This report was compiled to provide a concise handbook on the physical parameters of Finnish bedrock and to serve as a user guide to the application of petrophysical data. The aim was to provide some basic knowledge on the density and magnetic properties of rocks to enable better understanding of these properties and their correlation with geology, and to review summaries of these data to characterize different rock types. Petrophysical measurement practices are only briefly presented here, as their more detailed descriptions can be found in GTK's Quality Handbook concerning the Petrophysical Laboratory. SI units are used throughout the report.

2 GTK'S PETROPHYSICAL DATA PROGRAMME

2.1 Sample acquisition

Laboratory measurement of the petrophysical properties of rocks already started at GTK in the 1950s with the main objective being to support the interpretation of airborne geophysical survey data (Puranen et al. 1968). Petrophysical laboratories were established in the three regional offices of GTK – in Espoo, Kuopio and Rovaniemi – and measurement equipment was developed to create a computer-controlled measuring system (Puranen 1989a, b). Rock samples collected for geological mapping were routinely measured in petrophysical laboratories with the result that by the end of the 1970s, information on density and magnetic properties was available for over 41 000 samples. In order to complement the collection to cover different types of geological units all over Finland, a regional petrophysical mapping programme was carried out in 1980–1991 (Korhonen et al. 1989, Korhonen et al. 1993).

The number of petrophysically measured rock samples gradually grew and now covers the whole of Finland in an irregular net (Fig. 1). Samples have been acquired from different sources:

- Sample acquisition
  1. Samples acquired during the course of regional geological mapping of the Finnish bedrock;
  2. Samples collected by the Regional Petrophysical Sampling Programme 1980–1991 (Korhonen et al. 1989);
  3. Co-operation between the Nordic countries and Russia resulted in various geophysical and geological maps and databases (published 1986–1987); petrophysical sampling was also carried out and the measurement results from Finland were included in GTK's petrophysical register;

4. Sample collection from Ahvenanmaa provided by Prof. Carl Ehlers (sampling at 1-km intervals);
5. Another large group of petrophysical samples is the "lithogeochemical" dataset (Lahtinen & Korhonen 1996); for each geochemical sample, the density and susceptibility determinations are available.

- Sampling philosophy in the regional petrophysical mapping programme
  - Sampling sites were preselected by using airborne magnetic and electromagnetic maps and geological maps;
  - Source rocks of magnetic anomalies were localized using field magnetometers and kappameters;
  - Samples were collected from:
    - rocks corresponding to the main magnetic anomaly pattern types and electrical conductivity anomalies;
    - magnetically anomalous geological formations;
    - weakly magnetic regions between the anomalous rocks;
    - ore deposits (only discretionary and from outcrops to avoid their over-representation in statistics);
  - Variability in the internal susceptibility of outcrops was measured, archived and registered:
    - three representative samples were collected (usually by hammer) from an outcrop; these recordings are also archived and available;
    - the overall sampling density was 10–30 outcrops / 100 km2, corresponding to 30–90 samples / 100 km2;
  - If a sample was not available from an outcrop, a representative sample was selected, if possible, from drill cores in the study area;
  - Each sampling site was photographed.

- Sample positioning was originally based on 1:20 000 topographic base maps, but GPS positioning was later applied. Therefore, the accuracy of positioning varies for samples taken at different times.

The number and distribution of samples collected for petrophysical characterization of different rock types covered the whole of Finland (the goal was at least some samples from each 1:100 000 map sheet) and exceeded 130 000 samples by the end of the 1990s. Measurements of remanent magnetization started later than those of density and susceptibility, and hence the number of remanence determinations is only ~101 000. Since the early 2000s, bedrock samples for petrophysical measurements have usually come from different GTK projects or from external customers. A huge number of drill core samples from ore deposits measured from the beginning of the laboratory activities are not included in this database, but will be treated as a separate entity. All the petrophysical measurement data will in the near future be part of a new geological database at GTK (additional information by Eija Hyvönen (eija.hyvonen@gtk.fi).

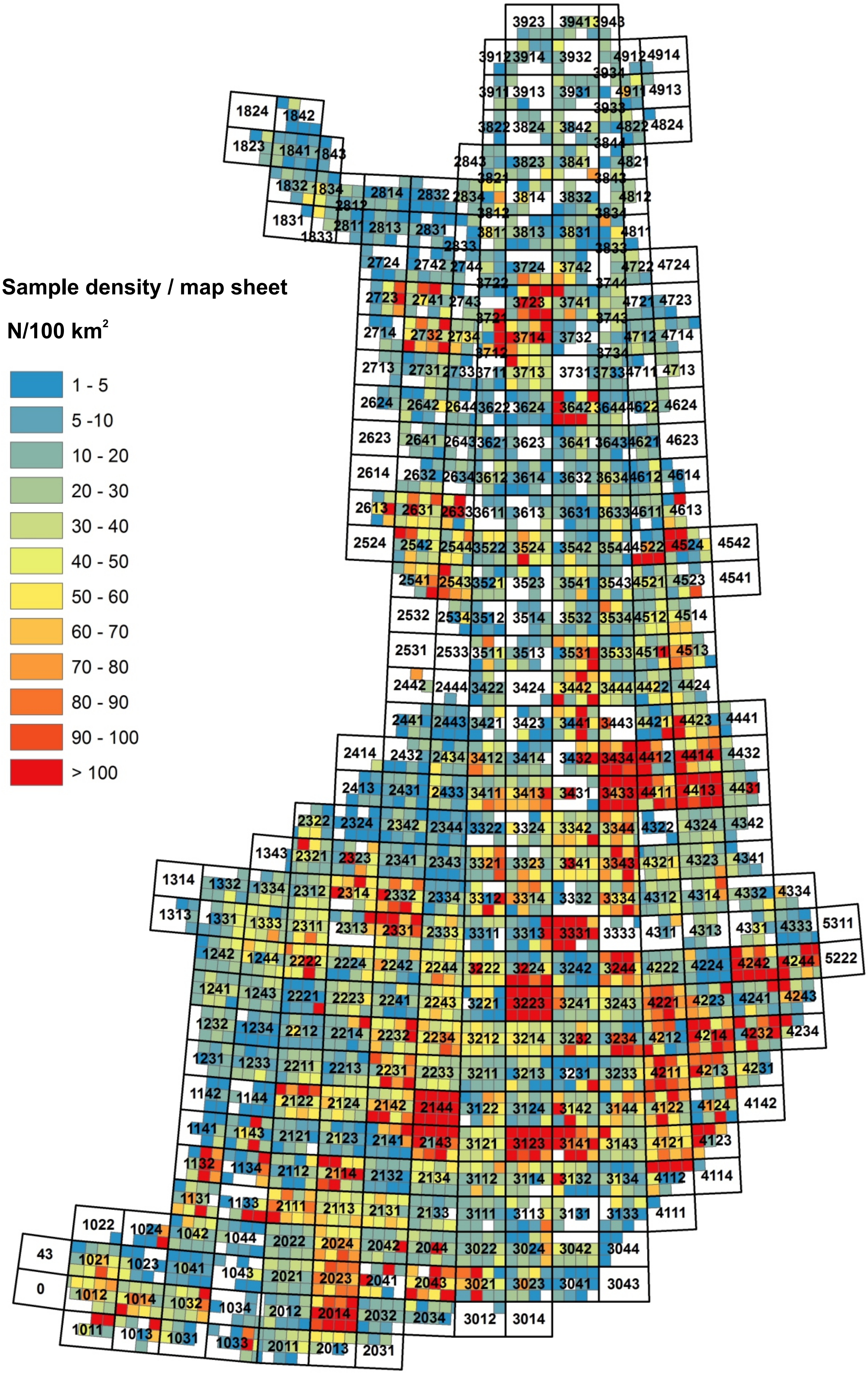


Fig. 1. Petrophysical sampling density in 1:20 000 map sheets. The average sample number is 19 samples/map sheet.

2.2 Measurements and variability of results

The measurement procedure was designed in such a way that no specific sample preparation is required for basic petrophysical measurements (density, magnetic susceptibility and the intensity of remanence). This method provides a rapid system for the measurement of a large number of samples with sufficient accuracy for the ordinary needs of geophysical interpretation and rock type classification. However, because of the large standard deviation of petrophysical properties, several samples are needed to provide statistical averages (see section 2.3). In terms of volume, samples of ca. 200 cm³ are optimal for standard measurements. The measuring equipment (Fig. 2) is described at http://www.gtk.fi/tutkimus/infrastruktuuri/geofysiikka (http://en.gtk.fi/research/infrastructure/geophysical).

Rock bulk densities are determined by weighing the samples in air and water. The standard error of repeated density determinations is less than 2 kg/m³. Because the sample is immersed in water, sample porosity may create a minor systematic error. However, this is normally below 1% for crystalline rocks (Henkel 1976, Kivekäs1993).

The susceptibility data are measured with a susceptibility bridge K-3A (Puranen & Puranen 1977), with standard errors of repeated measurements being about 10^{-9} m³/kg ($2.5–3·10^{-6}$ SI) for weakly magnetic samples, and about 2% for strongly magnetic samples (Puranen 1989). Magnetic susceptibility depends on the external magnetic field. The magnetic field used in measurements is of the same order of magnitude as the Earth's field. The field effect on the susceptibility in different parts of Finland may be only a few per cent. Because of the directional anisotropy of susceptibility, the susceptibility values depend on the direction of measurement, i.e. how the sample is placed in the measuring coil. The only limitation for the shape or size is that the samples fit inside the susceptibility coil (longest dimension < 10 cm). Standard susceptibility determinations are carried out for samples that are not field oriented and the sample is measured in a random direction. In the case of strong anisotropy, the variability in susceptibility between different directions may be even of the order of tens of per cent. The influence of shape irregularity can be reduced by collecting and measuring several samples from the same target to obtain the average susceptibility.

Fig. 2. Equipment for standard petrophysical determinations. From left: Low-field susceptibility bridge (inside the wooden box), computer control unit, balance, and flux-gate magnetometer inside a µ-metal shield. Photo: Satu Vuoriainen, GTK.

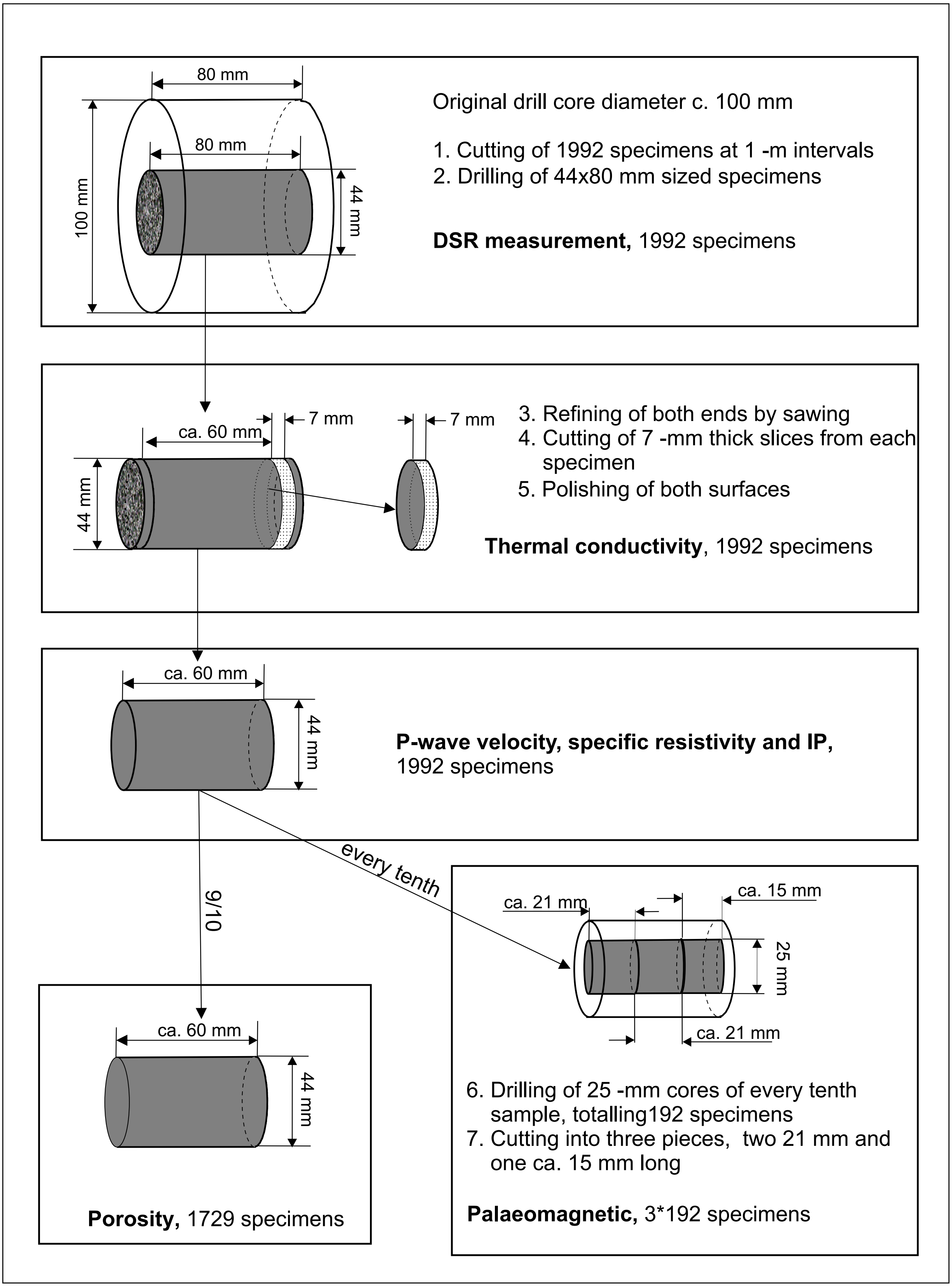


Fig. 3. Example of the sample preparation procedure for detailed petrophysical measurements of almost 2000 samples from the Outokumpu Deep Drill Core (Airo et al. 2011).

The intensity of natural remanent magnetization (NRM) is measured by R2 equipment (Puranen & Sulkanen 1985) with an error of less than 10% for average sample weights of 500 g. The threshold value is $20 \cdot 10^{-6}$ Am^2/kg, corresponding to values of 50-60 mA/m for the volume magnetization of average Finnish rock densities. Remanent magnetization (remanence) is field-dependent, so that the measurements are made using shield protection. The size and shape of the sample and the direction of measurement have a strong influence on the variability of the results. Uncertainty in the determination increases for samples that are much smaller than the optimum size, but can be corrected by increasing the sample size. Remanence is also sensitive to sample handling, e.g. striking with a hammer or other sharp shocks. In standard determinations of the intensity of remanence for irregular-shaped samples, the measurements are carried out in several – at least three – directions to obtain an average value. More detailed and accurate measurements of remanent magnetization can be gained by orientation of the samples and careful preparation to standard sizes.

For the other petrophysical measurements such as galvanic resistivity and P-wave velocity, the samples need to be specially prepared. For instance, the optimum sample preparation procedure illustrated in Figure 3 was designed for measurements of the Outokumpu Deep Drill Core samples (Airo et al. 2011a).

2.3 Petrophysical data collection

In the country-wide data collection of rock densities and magnetic properties, currently composed of more than 130 000 rock samples, the idea was to continuously cover different geological or geophysical provinces of each map sheet in Finland. Subsequently, the sampling has mostly been target specific. Furthermore, a new on-going sampling and measurement project (2012–2013) aims to complement the geophysical characteristics for different ore-deposit types in Finland. All petrophysical determinations, including the extra archived results from the beginning of the 2000s, will in near future be included in GTK's Mineral Reserve Service linked by http://gtkdata.gtk.fi/MDaE/index.html. Additional information is available by contacting Eija Hyvönen (eija.hyvonen@gtk.fi).

Each petrophysical sample is provided with information on the sampling site and the rock class, which is based on a hierarchical classification system that was updated by Korja (1989, see references therein). The six main rock classes are: 1 = plutonic (igneous), 2 = intrusive (dykes), 3 = volcanic, 4 = sedimentary, 5 = metamorphic, 6 = altered rocks and ore samples. The main classes are further divided into subclasses, each class possessing three lower hierarchical layers. Classification of igneous rocks is based on the recommendations of IUGS (International Union of Geological Sciences, http://www.iugs.org/). For example, the igneous rocks are divided into 10 main groups according to the highest hierarchy level given on the basis of the preliminary field classification, such as granitoids and rapakivis. The second hierarchy level is based on the modal composition of the samples (granite, tonalite, etc.). The next level takes into account the mineralogical or petrological variation of a rock type. The grouping of dykes is not based on any standard classification. Diabase and dolerite are regarded as synonyms, and lamprophyres, porphyry and pegmatite dykes form their own groups. Volcanic rocks are classified both on the basis of their mineral composition and their genesis. Sedimentary rocks are divided into clastic and precipitation sedimentary rocks. The grouping of metamorphic rocks is wide and non-homogeneous; there are, for example, schists, gneisses, migmatites, granulites, metaultramafites, greenstones, amphibolites, but also shock metamorphic, contact metamorphic and unmetamorphic rocks. The sub-division of graphite-bearing schists is based on the content of carbon and sulphur. Plutonic and metamorphic rocks are the dominant classes in the petrophysical database, with more than 45 000 granitoid samples and almost 20 000 gneiss samples (Table 1).

Originally, the field rock names were given by visual inspection at the sampling site, and these names were always checked and verified in the laboratory by a geologist. The naming was partly based on thin section studies. In some cases it was possible to give only an inaccurate name such as "schist" or "gneiss" if the rock type could not be specified in more detail. The purpose was that each sample could be classified at least to the main hierarchy level in order to compile the summaries.

Table 1. Number of samples for the six main rock classes represented by petrophysical data.

Rock class	Details	Number of samples
Plutonic	Felsic to ultramafic igneous rocks	64 500
Intrusive (dykes)	Mainly mafic dykes (dolerites/diabases)	5 650
Volcanic	Felsic to basaltic lavas and pyroclastics	5 300
Sedimentary	Different kinds of sedimentary rocks	2 100
Metamorphic	Gneisses, migmatites, schists etc.	52 300
Altered rocks and ore samples	Specific groups	400

2.4 Petrophysical parameters of different rock types

Petrophysical properties of rocks are a function of the minerals contained in the rock (Carmichael 1989). The most important parameters, density and magnetic properties, can be used to characterize different rock types, and they also reflect mineralogical changes due to geological processes. Porosity may have a role in some cases, in particular for weathered surface rocks or in some large-grained or highly altered rocks, but porosity is not generally significant in the Precambrian crystalline rocks. The main ("standard") petrophysical properties are:

- *Rock density,* describing the bulk mineral composition;
- *Magnetic susceptibility,* reflecting the iron and magnetite contents in rocks;
- *Remanent magnetization,* the magnitude of ancient magnetization.

The relationship between the total iron content and density for different felsic and mafic rocks has previously been presented by Puranen et al. (1978), and the magnetic properties for different Precambrian rock types have been discussed, for example, by Puranen (1989b) and Korhonen et al. (1993 and 1997). Puranen (1989b) examined the dependence of iron and magnetite contents on magnetic susceptibility and demonstrated the magnetically bimodal distribution of Finnish Precambrian rocks. He referred to the weakly magnetic group as "paramagnetic" and the strongly magnetic group as "ferrimagnetic". Korhonen et al. (1993) introduced in more detail the division of most rock types into the two magnetic populations, paramagnetic and ferrimagnetic, where the population limit is based on magnetic susceptibility. They also stressed that in ferrimagnetic rocks, remanent magnetization accounts for a greater portion of the total magnetization than induced magnetization. The effect of porosity on the density of Precambrian rocks was investigated by Kivekäs (1993). Comparisons and conclusions based on the "lithogeochemical" dataset were reported by Lahtinen and Korhonen (1996). They compared geochemical and petrophysical data on 403 bedrock samples from southern Finland as a means of correlating the mineralogy and chemical composition with the petrophysical properties of the rocks. Lahtinen's classification of rock types into different groups was adopted. Elo (1997) used density information in interpreting the gravity anomaly map of Finland. Petrophysical summaries for different rock types in Finland based on the database have previously been presented by Säävuori and Airo (2001). Summaries of petrophysical properties were largely reviewed in the Bouguer anomaly map (Korhonen et al. 2002a) and the magnetic anomaly map (Korhonen et al. 2002b) of the Fennoscandian shield. These data collections are available in all Nordic countries, and the Finnish part is included in GTK's petrophysical data collection.

2.5 Petrophysical characterization of ore deposit types in Finland

In addition to typical bedrock samples, the petrophysical data collection also contains some information on samples collected from ore deposits and exploration targets. Mineralized samples were included in the petrophysical register only to give juxtaposition for ordinary rocks. GTK has a wide register of ore-deposit petrophysics, mainly measured from drill cores, but these will be dealt with as a separate entity. For example, the petrophysical register contains more than 700 samples from metamorphosed black shales, or "black schists". They were mainly sampled for bedrock mapping, but some of them may contain variable proportions of sulphides. Because metamorphosed black shales may host sulphide mineral deposits, their physical properties have been intensively studied (Airo 1997, Airo & Loukola-Ruskeeniemi 2004). Arkimaa et al. (2000) used the data when compiling the black shale map of Finland. A new black shale database, including geochemical and petrophysical analyses of >400 black shale core samples, will be published in the near future (Loukola-Ruskeeniemi et al. 2011, Hyvönen et al. 2013). In addition, magnetic properties and mineral magnetism of Au prospective greenstones in northern Finland were investigated by Airo and Mertanen (2008) with the result that the magnetically destructive ore-forming process could be connected to the post-orogenic period. The ongoing GTK project (2012–2013) "Geophysical characteristics of ore deposit types in Finland" aims to improve knowledge of the key geophysical parameters that may be utilized in studies on ore-forming processes. The studies are based on detailed petrophysical investigations, also including measurements of electrical conductivity and mineral magnetism.

3 PETROPHYSICAL CHARACTERISTICS OF FINNISH BEDROCK

3.1 Density

The density of a rock depends on its main mineral composition and porosity. In Precambrian crystalline basement rocks, the porosity is commonly very low (<5%) and has no substantial effect on rock densities (Kivekäs 1993). In the petrophysical database, the mean densities of Finnish rock types

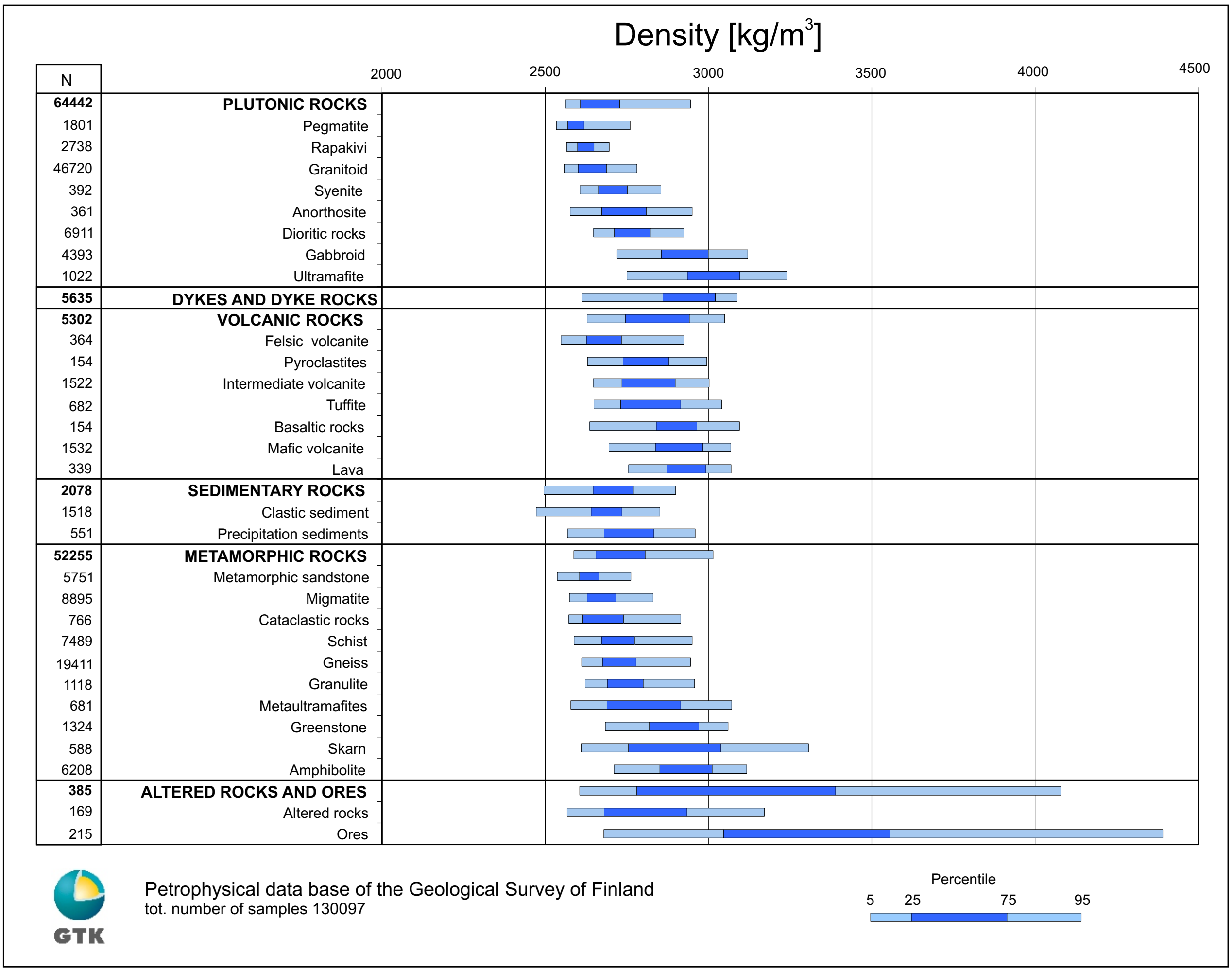


Fig. 4. Variability in density for different rock classes. Note that 90% of sample densities lie within the range indicated by the blue line. About 50% of sample densities fall within the dark blue range. The rock type classification is explained in the text.

are typically between 2500–3200 kg/m³. The densities of felsic (silicic) rocks are characterized by densities below 2700 kg/m³ and mafic rocks by densities above 2800 kg/m³. In each main rock class, the mean densities increase due to an increase in mafic minerals and reflect the iron content (Fig. 4).

3.2 Magnetic susceptibility

Magnetic susceptibility (*k*) is a measure of the ability of a rock to become magnetized when exposed to an external magnetic field. Susceptibility depends on the geochemistry and mineralogy of a rock and may be affected by later metamorphic processes and alteration. A summary of magnetic volume susceptibilities in Finland (Fig. 5) shows the division of each rock type into two main magnetic categories: the weakly magnetic (paramagnetic) and the strongly magnetic (ferrimagnetic) population. Generally speaking, about 75% of the samples fall into the paramagnetic population. The third category, small in number, with negative susceptibilities due to a large proportion of diamagnetic minerals, is typical for certain rock classes. This division into two main magnetic

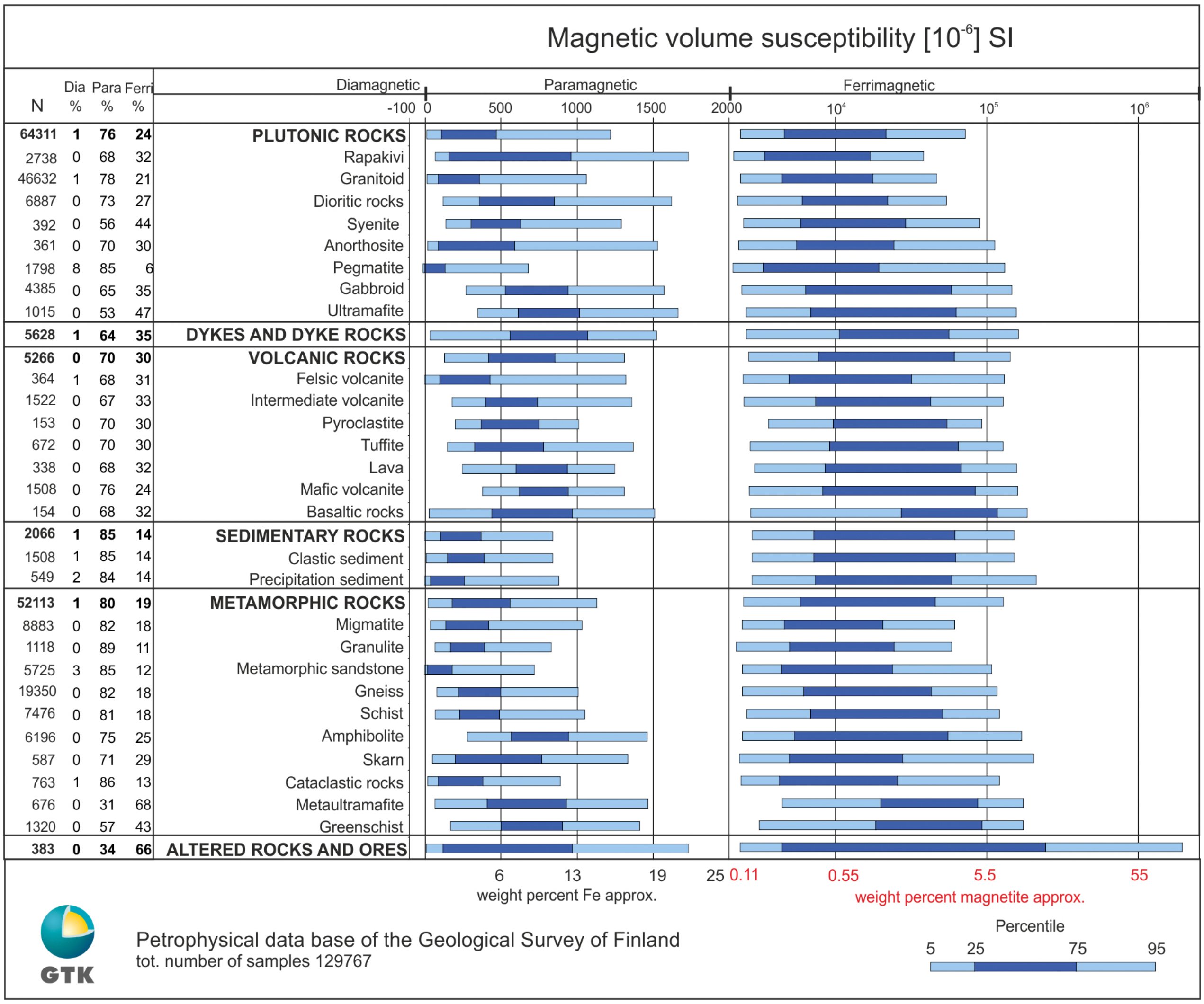


Fig. 5. Variability in magnetic susceptibility (*k*) for different rock classes. The division of susceptibility into three classes is based on the following cut-off values: diamagnetic $k < 0$; paramagnetic $k = 0–0.002$ (SI); ferrimagnetic $k > 0.002$ (SI). Note that 90% of sample susceptibilities lie within the range indicated by the blue line, and 50% of sample susceptibilities fall within the dark blue range. In this respect, there is no gap between paramagnetic and ferrimagnetic ranges, although this appears to be the case in the diagram. The horizontal bottom axis shows the approximate weight per cent of Fe (in black) in the paramagnetic range and, correspondingly, the approximate weight per cent of magnetite (in red) in the ferrimagnetic range. It follows that the susceptibilities are the same for samples containing either 25 weight-% Fe or 0.11 weight-% magnetite. The rock type classification is explained in the text.

populations is typical for metamorphosed Precambrian rocks. In the paramagnetic category, the content of ferrimagnetic minerals is very low and the susceptibilities are mostly due to paramagnetic mafic silicates. The strongly magnetic categories carry ferrimagnetic minerals, which dominate the magnetic susceptibility even when present in small concentrations. In general, the range of magnetic properties is wide, and the distributions are therefore commonly presented on a logarithmic scale.

Susceptibility determinations from irregular-shaped samples may show variability. If the anisotropy of susceptibility is strong, repeated measurement may not give the same result because of the random measurement direction. The effect of shape and size on susceptibility can be reduced by calculating the mass susceptibility, e.g. to allow the use of a geochemical correlation, instead of using volume susceptibility (Puranen 1989). A detailed discussion of the factors affecting magnetic susceptibility was presented by Hrouda et al. (2009) in their demonstration of the usefulness of hand-held magnetic susceptibility meters in solving various geological problems. They outlined that para- and diamagnetic susceptibilities are independent of the magnetic field, while ferromagnetic susceptibility is field-dependent. Because of this effect, the susceptibilities measured in different fields are incomparable. In the petrophysical laboratory, susceptibility is measured using the field that corresponds to the present Earth's magnetic field in Finland (~41 A/m), in which the magnetization is directly proportional to the field intensity and the instruments measure the field-independent susceptibility in all minerals. In the following, some basic issues that affect magnetic susceptibility are summarized.

Magnetic susceptibility of rock-forming minerals:
- may vary widely depending on the chemical composition;
- depends on the ratio of Mg and Fe;
- in titanomagnetites, depends on the amount of titanium.

Paramagnetic susceptibility of rocks depends on:
- the relative proportion of mafic / felsic minerals;
- the total iron content in the rock-forming minerals.

Ferrimagnetic susceptibility of rocks depends on:
- the content of iron (in a complex way);
- magnetic mineralogy and content (Table 2);
- the magnetizing field (ferromagnetic susceptibility);
- temperature: The Curie temperature is the critical temperature for each ferrimagnetic mineral, at which it looses its magnetization. This has no role in the ambient temperatures for most minerals.
- the grain size of ferrimagnetic minerals: Susceptibility decreases when the grain size diminishes from multi-domain grains to the limit of the so-called single domain grains (differs between minerals).

In almost all rock classes, the susceptibility value represents the mean or average value of two magnetic categories. For example, the magnetic susceptibilities of Proterozoic mafic dykes in Finland depend on the metamorphic grade and degree of alteration. The non-metamorphosed Häme dyke swarm in southern Finland is composed of several dykes with homogeneous magnetic properties, and thus contains only the high-susceptibility category (Airo 1999b). On the contrary, the altered Kuhmo dykes have weak magnetic susceptibilities because of the decreased content of magnetite.

Table 2. Magnetic materials and susceptibility.

Type of magnetic materials	Mineral carriers	Magnetic susceptibility
Ferrimagnetic	Magnetite, monoclinic pyrrhotite	Positive, often very high, complex function of the magnetizing field
Antiferromagnetic	Hematite	Positive, relatively low
Paramagnetic	Rock-forming Fe,Mg-bearing silicates	Positive, relatively low, independent of the magnetizing field
Diamagnetic	Quartz, calcite, graphite, tremolite	Negative and independent of the magnetizing field

3.3 Induced magnetization

Induced magnetization can be calculated on the basis of susceptibility (not included in the standard database, but available) and is defined as:

$$\mathbf{M}_i = k\mathbf{H}$$

where $\mathbf{M}_i$ is the vector of the induced magnetization (in A/m in SI units), $\mathbf{H}$ is the vector of the magnetic field (in A/m) and k is the magnetic susceptibility (dimensionless).

The summary for induced magnetization in Figure 6 shows generally high values for mafic igneous rocks and for different groups of volcanic rocks. The values for sedimentary rocks and for certain metamorphic rocks (e.g., granulite, migmatite, gneiss, schist, amphibolite) are generally low. In the groups of greenschists, metaultramafites and altered rocks and ores, the induced magnetization values are higher than those of igneous rocks. The wide ranges for all these groups, however, indicate wide variability in the content of mafic minerals and magnetic minerals.

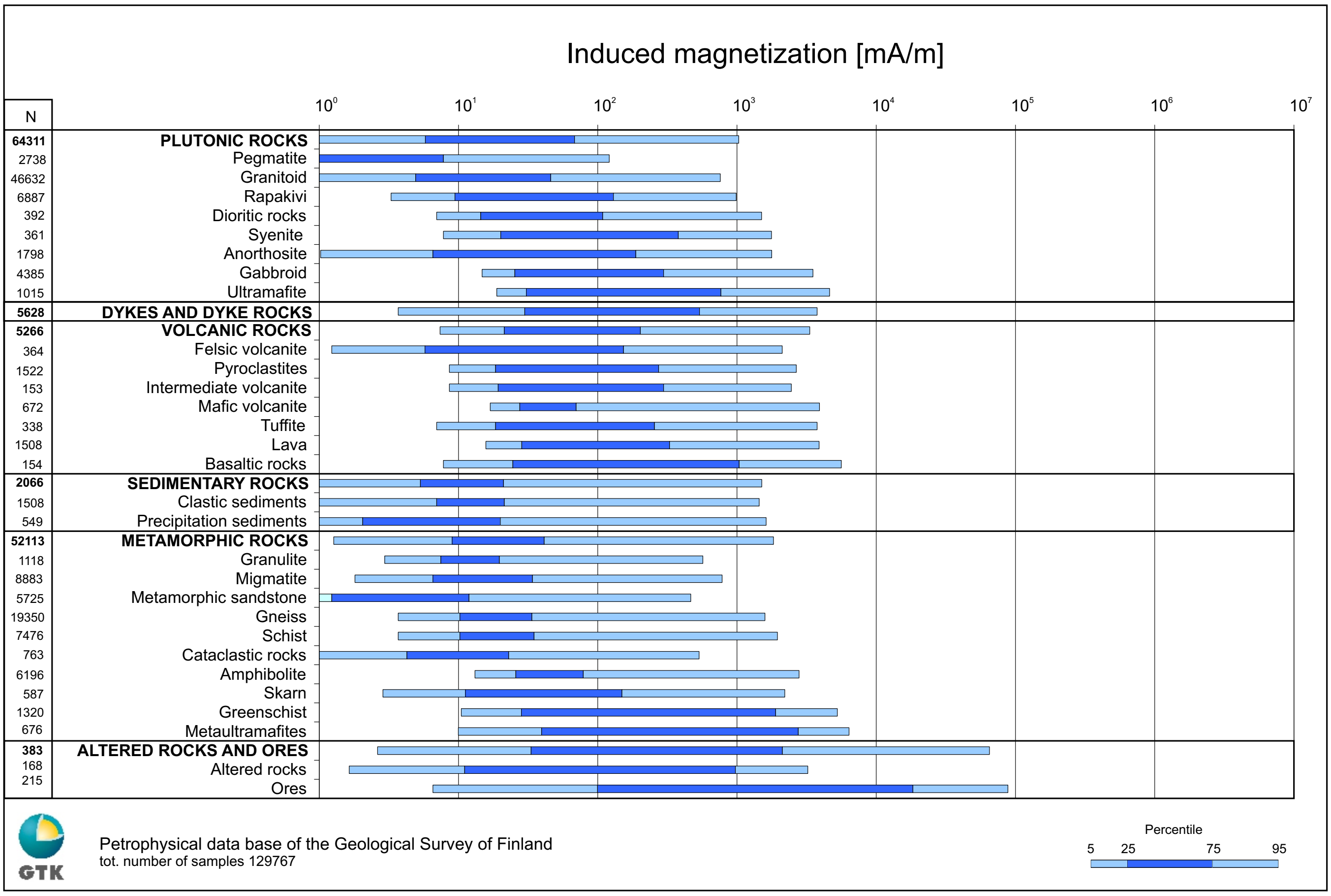


Fig. 6. Variability in induced magnetization for different rock classes. Note that 90% of induced magnetization values lie within the range indicated by the blue line, and 50% of them fall within the dark blue range. The rock type classification is explained in the text.

3.4 Remanent magnetization

Rocks that contain ferrimagnetic minerals are characterized by the existence of a permanent, "residual" magnetization that exists even though the external field has been removed. Measurements of the intensity of remanent magnetization are protected from the Earth's field by a shield and in several (at least 3) directions. The results are given in A/m and depend on the content, grain size and shape of ferrimagnetic minerals that can carry remanence, i.e., minerals with a specifically ordered magnetic structure. Natural remanent magnetization is a vector sum of remanence components

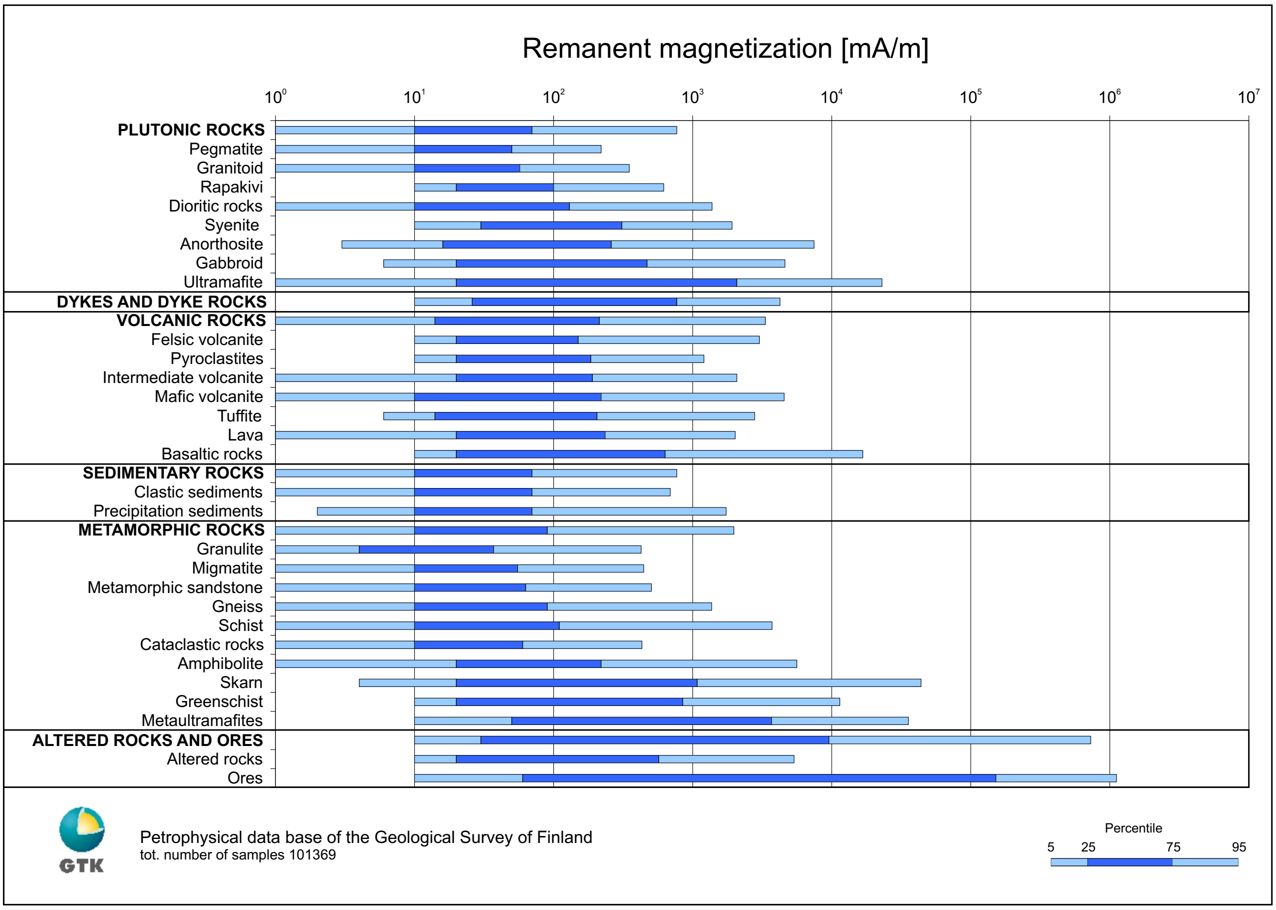


Fig. 7. Variability in the intensity of remanent magnetization for different rock classes. Note that 90% of remanent magnetization values lie within the range indicated by the blue line, and 50% of them fall within the dark blue range. The rock type classification is explained in the text.

acquired by the rock at different times under different magnetic fields. In addition to the primary remanence acquired when the rock was formed, it possesses a secondary remanence component, e.g. thermoremanence, introduced as a result of metamorphic processes. Therefore, each rock type possesses variability in remanence intensities and directions, unless they were formed under similar circumstances.

The intensities of remanent magnetization for different rock types (see summary in Fig. 7) show quite a similar histogram to that of induced magnetization. In the class of metamorphic rocks, however, the remanent magnetizations are higher than the induced ones. One reason for this is the increased proportion of fine-grained magnetite in prograde metamorphic processes.

3.5 Total magnetization

The intensity of total magnetization $\mathbf{M}_t$ of a rock (in A/m) accounts for the magnetic anomaly intensity and is important in the interpretation of magnetic data. It is not included in the standard database, but can be calculated as the vector sum of the induced magnetization $\mathbf{M}_i$ and the remanent magnetization $\mathbf{M}_r$:

$$\mathbf{M}_t = \mathbf{M}_i + \mathbf{M}_r$$

Figure 8 compares induced and remanent magnetizations calculated from the arithmetic averages for different rock types. The comparison is limited to only those rock types whose susceptibility exceeds 0.002 (SI). It shows that remanent magnetization accounts for >50% of the total magneti-

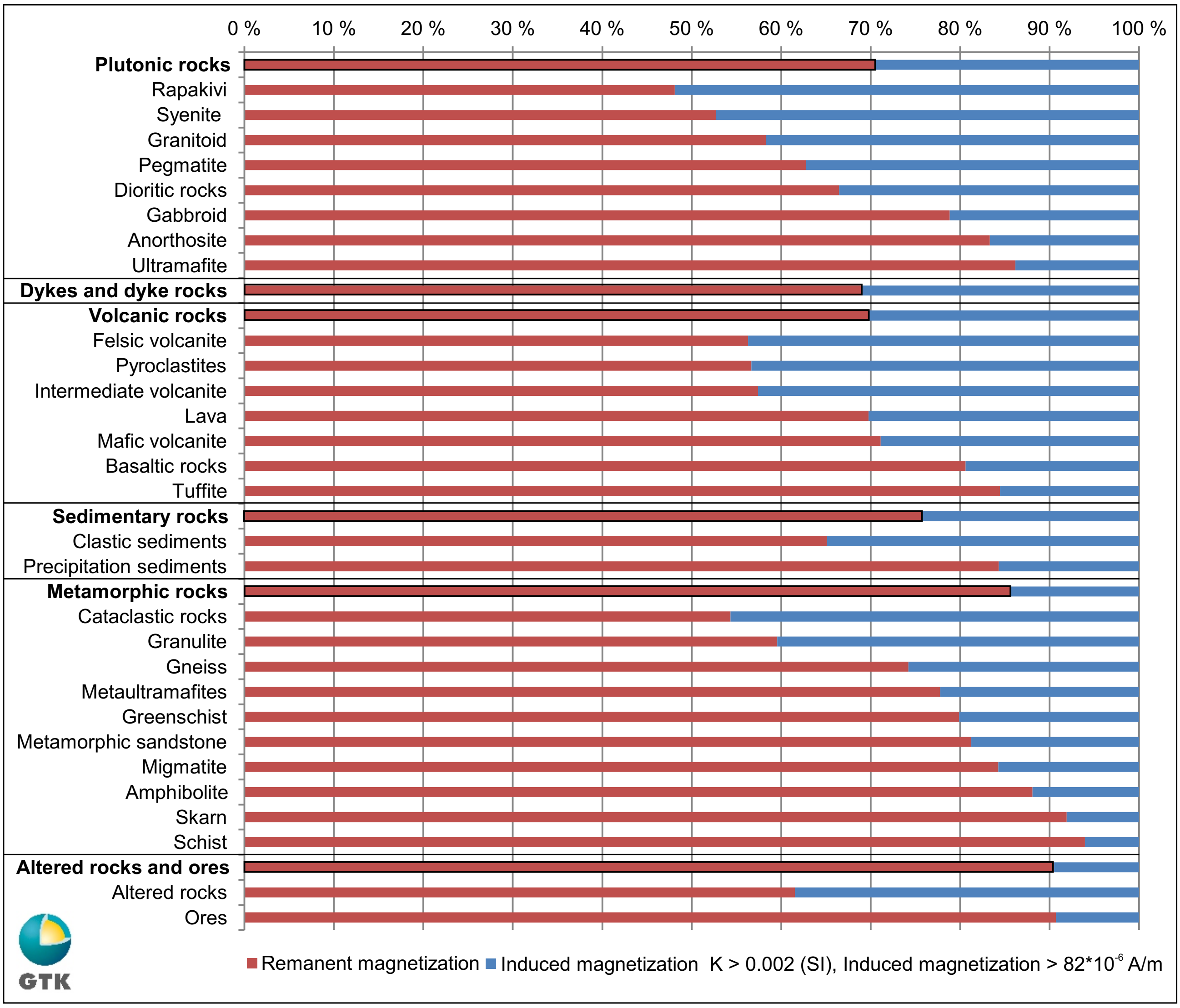


Fig. 8. Comparison of induced and remanent magnetizations for different rock classes. Only samples in the ferrimagnetic class ($k > 0.002$ (SI) were chosen for this comparison. The rock type classification is explained in the text.

zation for almost every rock type and is especially significant for metamorphic rocks. Even the group of rapakivi granites has two magnetic variations, and the magnetic variation within different rapakivi plutons in Finland may be distinctive (Karell et al. 2009).

3.6 Königsberger ratio (Q-ratio)

The Königsberger ratio Q is mainly used in two ways for the geological interpretation of petrophysical parameters: 1) to estimate the magnetic mineral type and grain size in a rock sample (e.g., magnetite or pyrrhotite), and 2) to evaluate how dominant the remanent magnetization is for the magnetic anomaly related to the rock unit. If the remanence dominates (Q-ratios >> 1), it may be important to consider the direction of magnetization in the interpretation. For example, if the direction deviates much from the direction of the present Earth's magnetic field, the effect on the magnetic anomaly intensity and shape may be substantial.

The Q-ratio is defined as the ratio of the magnitude of remanent magnetization to the magnitude of induced magnetization:

$$Q = |\mathbf{M}_r| / |\mathbf{M}_i| = M_r / M_i$$

where the induced magnetization depends on magnetic susceptibility k and the intensity of the inducing magnetic field (H).

A summary of the Q-ratios for different rock types in Finland is presented in Figure 9. In general, the Q-ratios are only relevant for rock samples that contain ferrimagnetic minerals, indicated by sufficiently high susceptibilities. The Q-ratio was only calculated for ferrimagnetic samples, with the lowest susceptibility limit set as $k > 0.002$ (SI). The range of Q-ratios then falls mainly between 0.01 and 100. Commonly, rocks with coarse-grained magnetite as their main magnetic mineral exhibit a low Q-ratio of <1. These rocks include felsic igneous rocks and different types of volcanic rocks. A higher Q-ratio indicates the content of monoclinic pyrrhotite or fine-grained magnetite. For example, the rock class 'schist' has a Q-ratio of 10–100. This suggests pyrrhotite as the main ferrimagnetic mineral.

Because the ferrimagnetic susceptibility is field-dependent, Königsberger ratios also depend on the magnetic field at the study site. There are various possible methods of calculation, and these may cause some small deviation. No exact value can be given for the Q-ratio of a particular sample, because its value depends on the place and time of determination. Therefore, there may be variability even in repeated measurements. Isolines of the intensity of magnetic flux density (B) and magnetic field (H) over Finland in 1985 are compared in Figure 10. Their definition is based on the formula presented by Suksdorff et al. (1986). Both B and H may be used in the calculation of the Q-ratio, but although their variability in Finland is low, the resulting Q-ratios may deviate from each other by some orders of magnitude. In order to interpret and compare geophysical anomalies, we propose to use the *in situ* magnetic field for the calculation of Q-ratios. On the other hand, when comparing different rock classes and in studies on their magnetic mineralogy, it is important to use Q-ratios calculated by using the same magnetic field value for all of them. In interpretation, the direction of magnetization is often regarded as parallel to the Earth's field, but the directional anisotropy of remanent magnetization, as well as of magnetic susceptibility, may affect the magnetic signature.

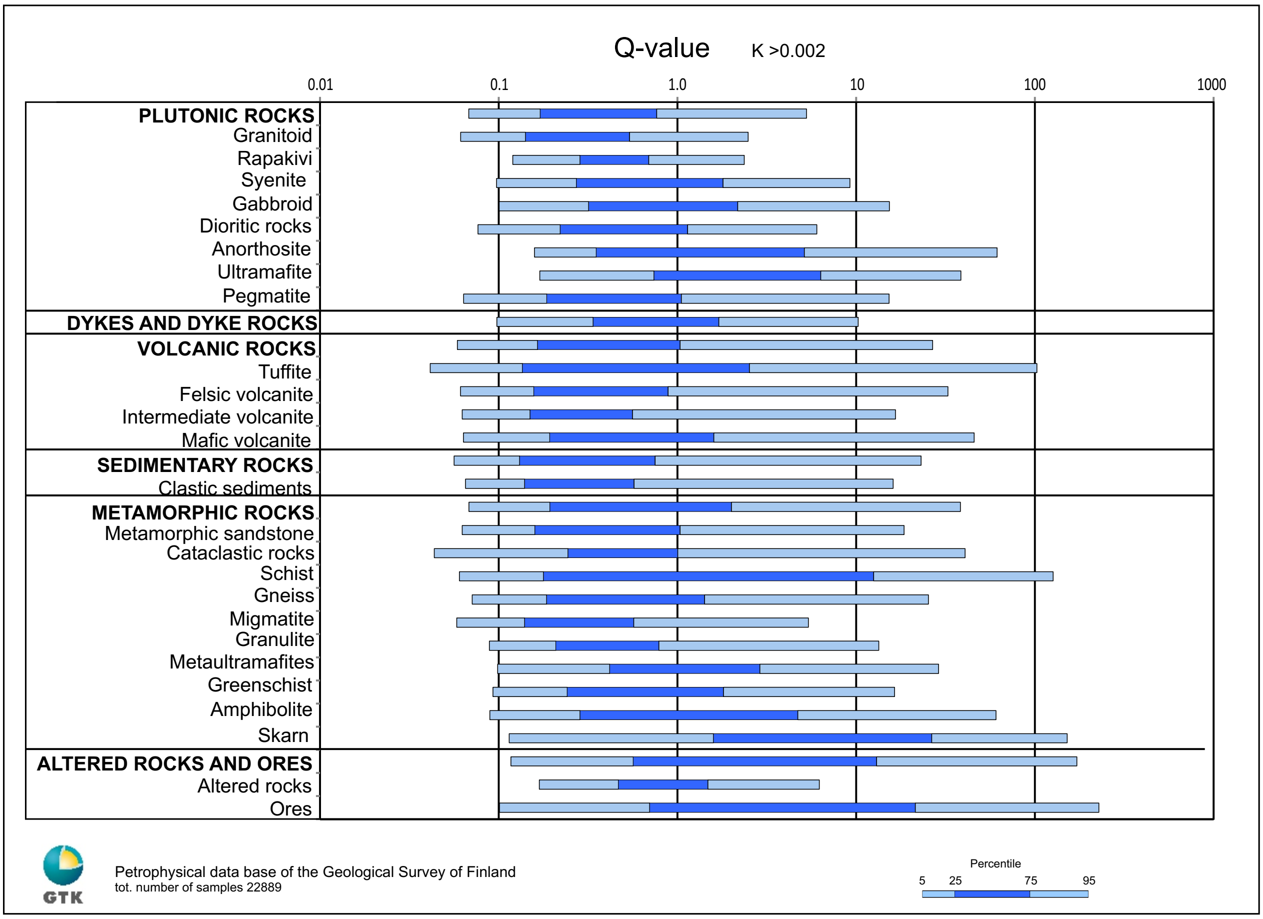


Fig. 9. Variability in Q-values for different rock classes. Only samples in the ferrimagnetic class ($k > 0.002$ (SI)) were chosen for this comparison. The rock type classification is explained in the text.

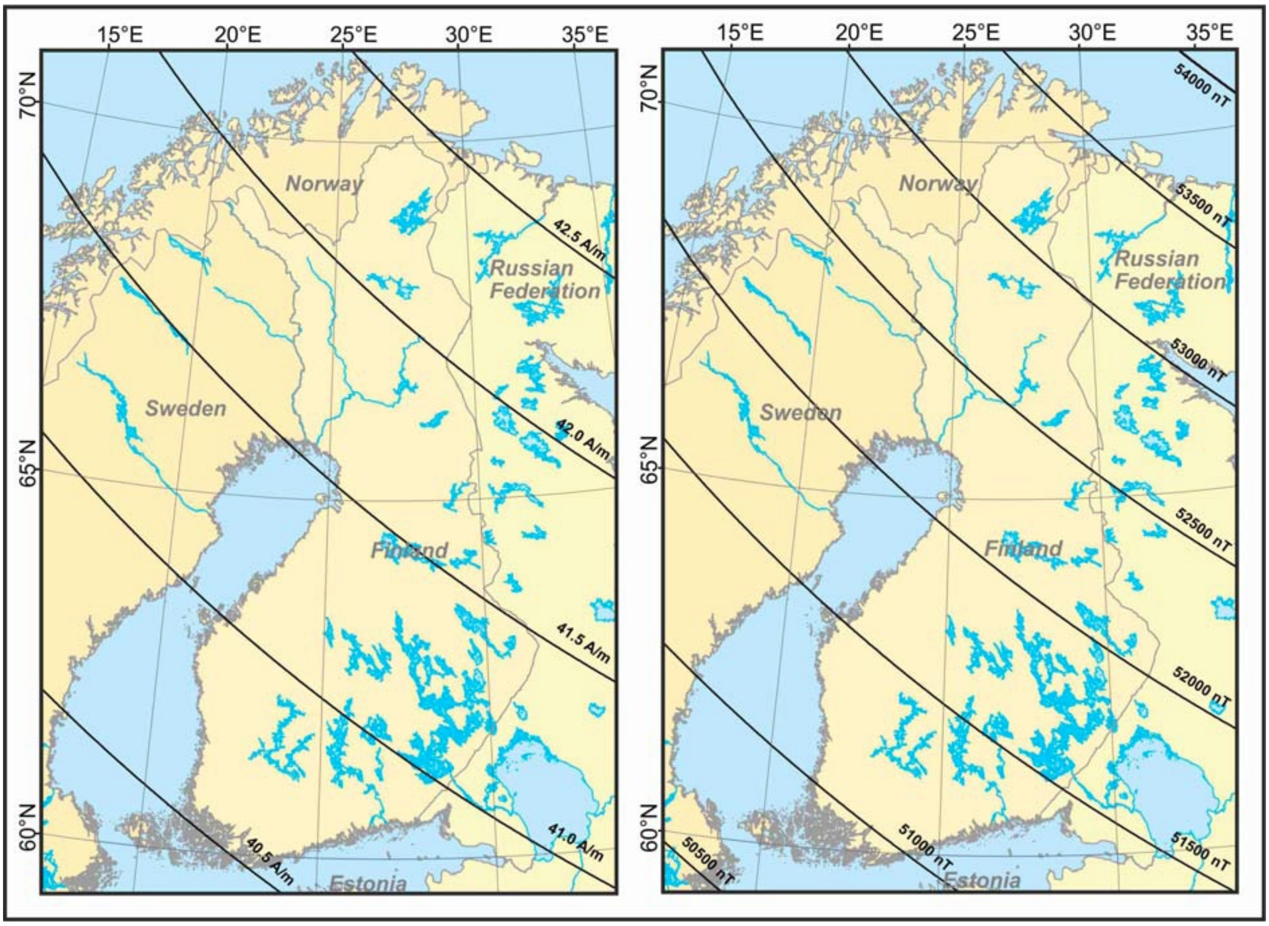


Fig. 10. Isolines of the magnetic field *H* (A/m) (left) and the magnetic flux density *B* (nT) (right) over Finland in 1985. Their definition is based on the formula presented by Sucksdorff et al. (1986).

3.7 Magnetic anomalies

The relationship between remanent and induced magnetization and their influence on the Q-ratio and the amplitude of the magnetic anomaly is compared in Figure 11. The anomaly calculation is based on the formula presented by Sucksdorff et al. (1986):

$$F_{max} = 1/2 \times (k + M_r/H) \times \Delta F$$

where k is magnetic susceptibility (SI), M_r is the intensity of remanent magnetization (A/m), H is the intensity of the magnetic field (A/m), and ΔF is the magnetic anomaly intensity (nT).

Ferrimagnetic rocks are responsible for magnetic anomalies. Figure 11 compares the magnetic properties of the ferrimagnetic ($k > 0.002$ SI) samples representing 30 main rock type categories in the measurement collection. The range of Q-ratios for all rocks types is mainly distributed between 0.1 and 10. Low Q-ratios of <1 commonly reflect rocks that contain magnetite of a coarse grain size, for example mafic igneous rocks such as undeformed gabbros or dolerites (diabases). Metaperidotites and graphitic schists may have still higher Q-ratios. The other three diagrams show that the Q-ratios of plutonic rocks, metamorphic rocks and volcanic rocks are between 1 and 10. The diagram thus verifies that the remanent magnetization has higher importance than the induced magnetization in producing high magnetic anomalies with an intensity of 1000–10 000 nT. The majority of magnetic anomalies visible on aeromagnetic maps are due to the strongly magnetic (ferrimagnetic) population. The weakly magnetic (paramagnetic) population normally causes magnetic anomalies of less than 50 nT, but ferrimagnetic minerals also present in this population may occasionally cause higher anomalies.

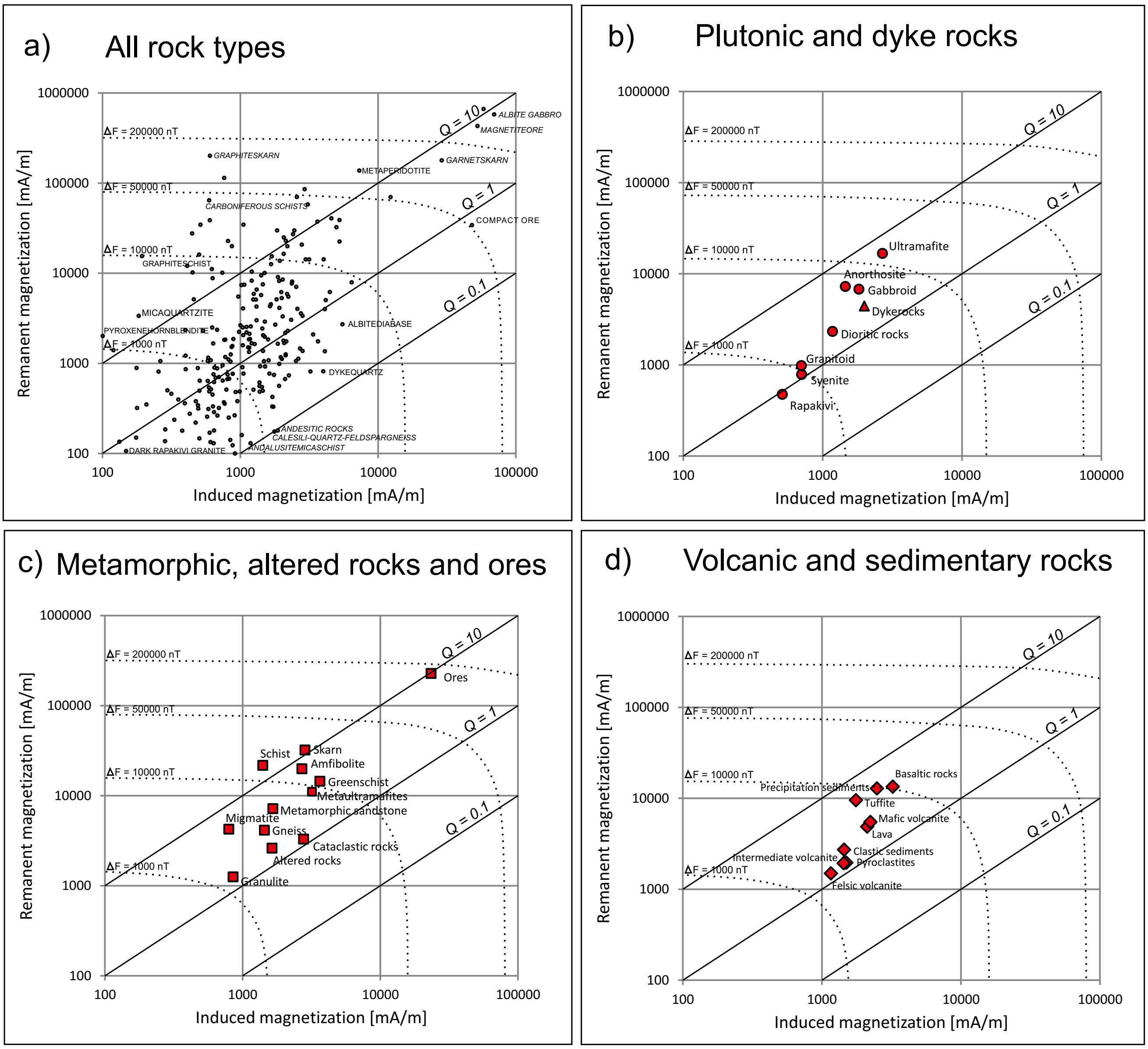


Fig. 11. Comparison of induced and remanent magnetizations, Q-ratios and the corresponding calculated magnetic anomaly intensities for ferrimagnetic samples representing different rock types. The rock type classification is explained in the text.

4 PETROPHYSICAL MAPS

4.1 Regional petrophysics

Petrophysical data can be used in regional tectonic studies together with airborne geophysical data for characterizing tectonic basement blocks (Airo 1999a). This type of analysis is possible if the petrophysical sampling density is adequate and if the geological units to be characterized are large enough and are mineralogically homogeneous enough. The correlation of petrophysics with airborne geophysics may also provide ideas on the mineralogy of rocks (Airo 2005, Airo et al. 2011b). The problem in regional investigations is the irregularity of petrophysical sampling. Some outcrops may be represented by numerous samples, while others may not have been sampled. Pirttijärvi et al. (2013) presented a numerical method for the interpolation of irregularly sampled petrophysical data. Information from digital geological maps is used to constrain the interpolation onto an evenly sampled grid. The gridding is based on inverse distance weighting and a moving window strategy. The proportional surface areas of the lithological units inside the investigation area are used as basic areal weights that aim to reduce the effect of outcropping geological formations with a small surface area but a large number of samples. Compared to traditional interpolation methods, lithological weighting produces maps that are more meaningful geologically, particularly in those areas where only few rock samples are available.

4.2 Distribution of para- and ferrimagnetic samples

The primary aim of collecting petrophysical samples was to aid the interpretation of aeromagnetic maps in Finland. It was soon discovered that almost all rock types in Finland show both magnetic and non-magnetic varieties. Puranen (1989) divided Finnish Precambrian rocks magnetically into weakly and strongly magnetic populations referred to as paramagnetic and ferrimagnetic. The paramagnetic population was defined by the linear part of the average density-mass susceptibility diagrams. The boundary value varies from 22 to $52 \cdot 10^{-8}$ m^3/kg (mass susceptibility) for the different rock types. However, as noted by Lahtinen and Korhonen (1996), even the most paramagnetic samples show a small ferrimagnetic component (on average $2 \cdot 10^{-8}$ m^3/kg), and pure paramagnetic samples are either rare or absent.

The distribution of the ferrimagnetic source rocks producing the aeromagnetic anomalies compared with the paramagnetic varieties can be quickly checked from the petrophysical database. Figures 12–15 display examples where the ferrimagnetic samples belonging to the rock groups of mafic and ultramafic dykes (Fig. 12), volcanic rocks (including different sub-groups of volcanic rocks, Fig. 13), ultramafic rocks (Fig. 14) and carbonatites or carbonate sedimentary rocks (Fig. 15) were sampled. The susceptibility of 0.002 (SI) was here used as the boundary value between para- and ferrimagnetic groups. The outlines of rock classes are based on the digital base map of Finland (http://www.geo.fi/en/bedrock.html). A closer view of example formations is given in the attached detailed maps (Figs. 12–15).

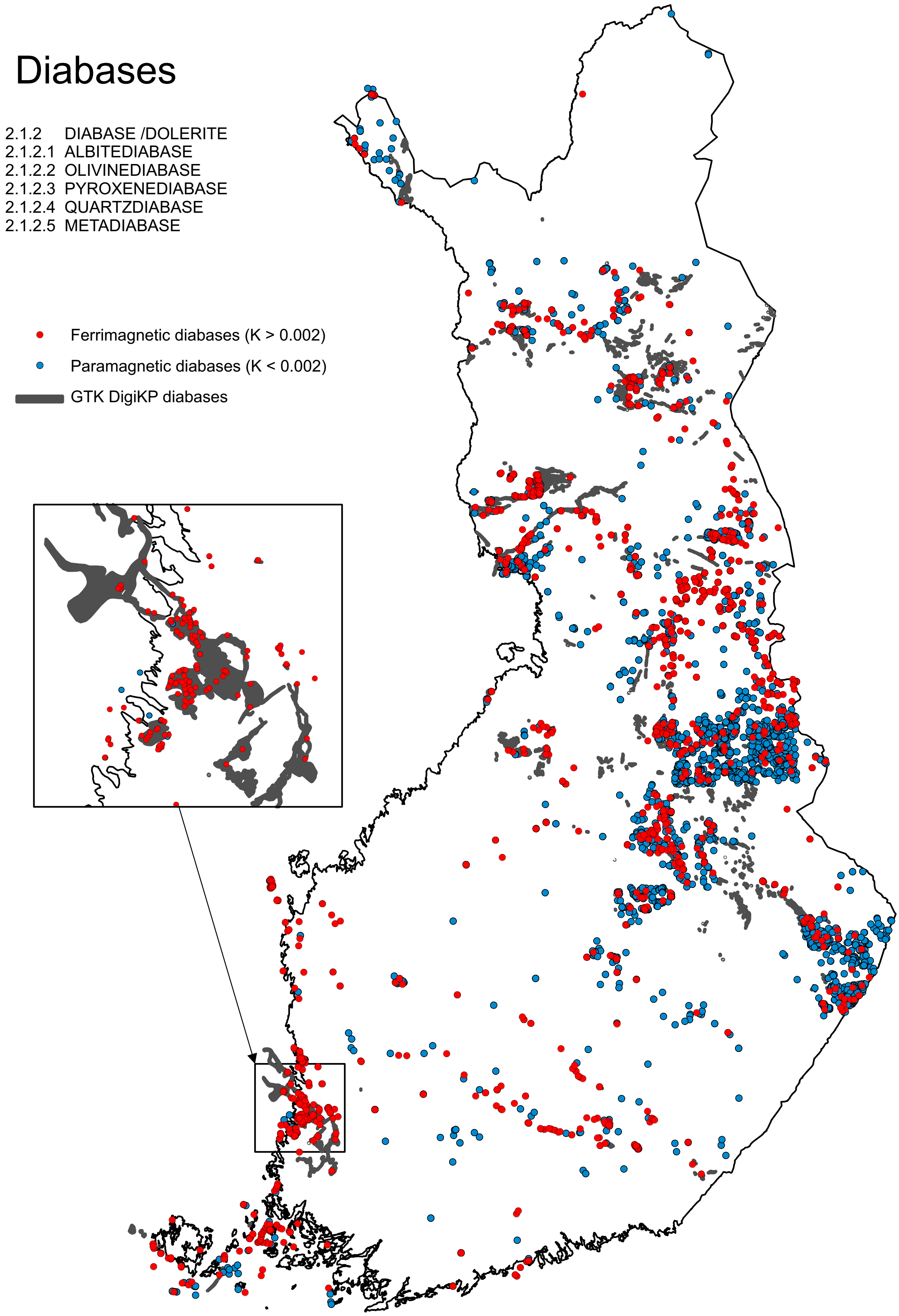


Fig. 12. Mafic and ultramafic dyke rock samples ("diabases"). Grey areas show the distribution of mafic and ultramafic dyke rocks in the digital map database. Green dots denote paramagnetic and red dots ferrimagnetic petrophysical samples. Where the locality is the same, the ferrimagnetic samples are shown on top of the paramagnetic ones.

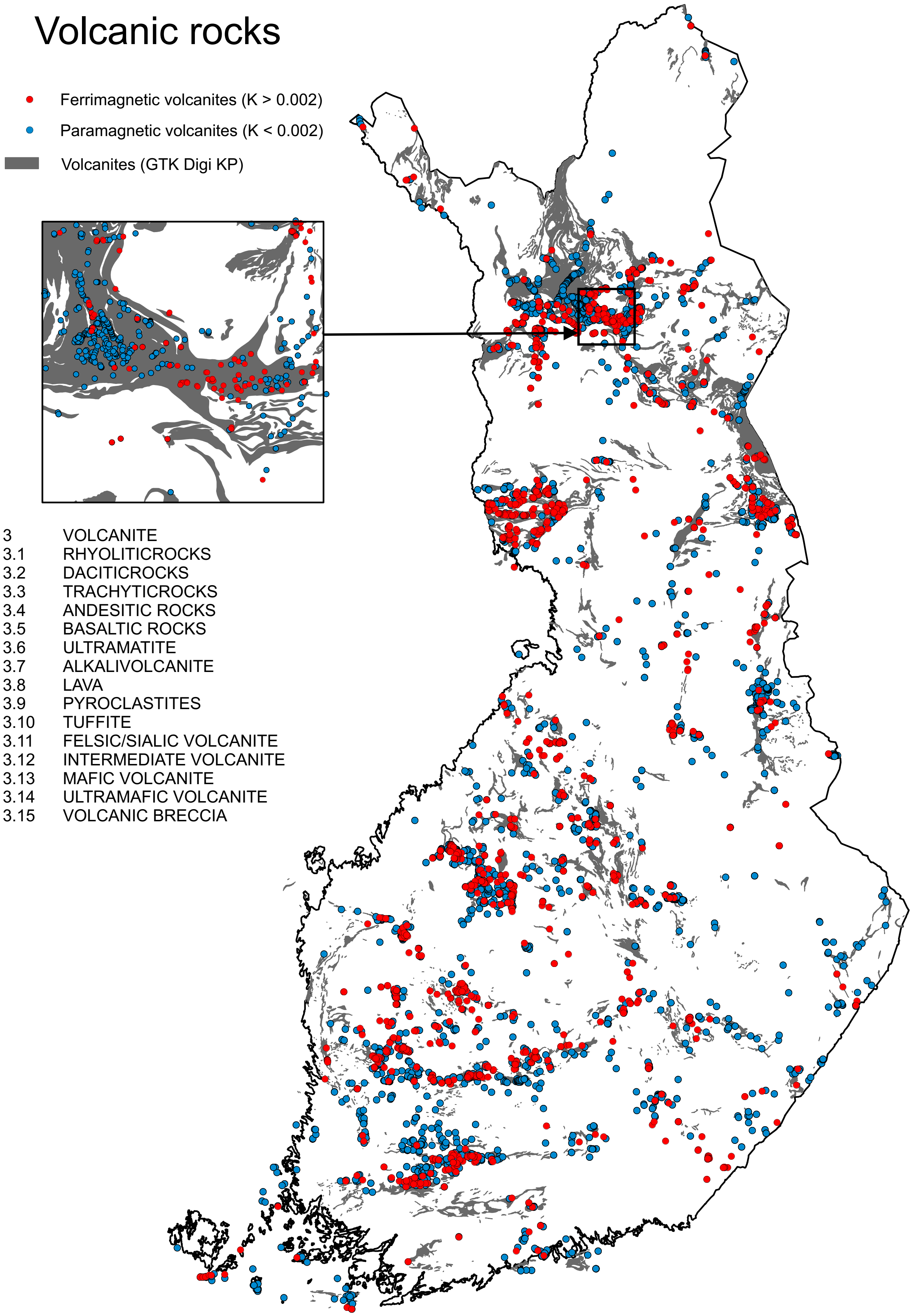


Fig. 13. Volcanic rock samples. Grey areas show the distribution of volcanic rocks in the digital map database. Green dots denote paramagnetic and red dots ferrimagnetic petrophysical samples. Where the locality is the same, the ferrimagnetic samples are shown on top of the paramagnetic ones.

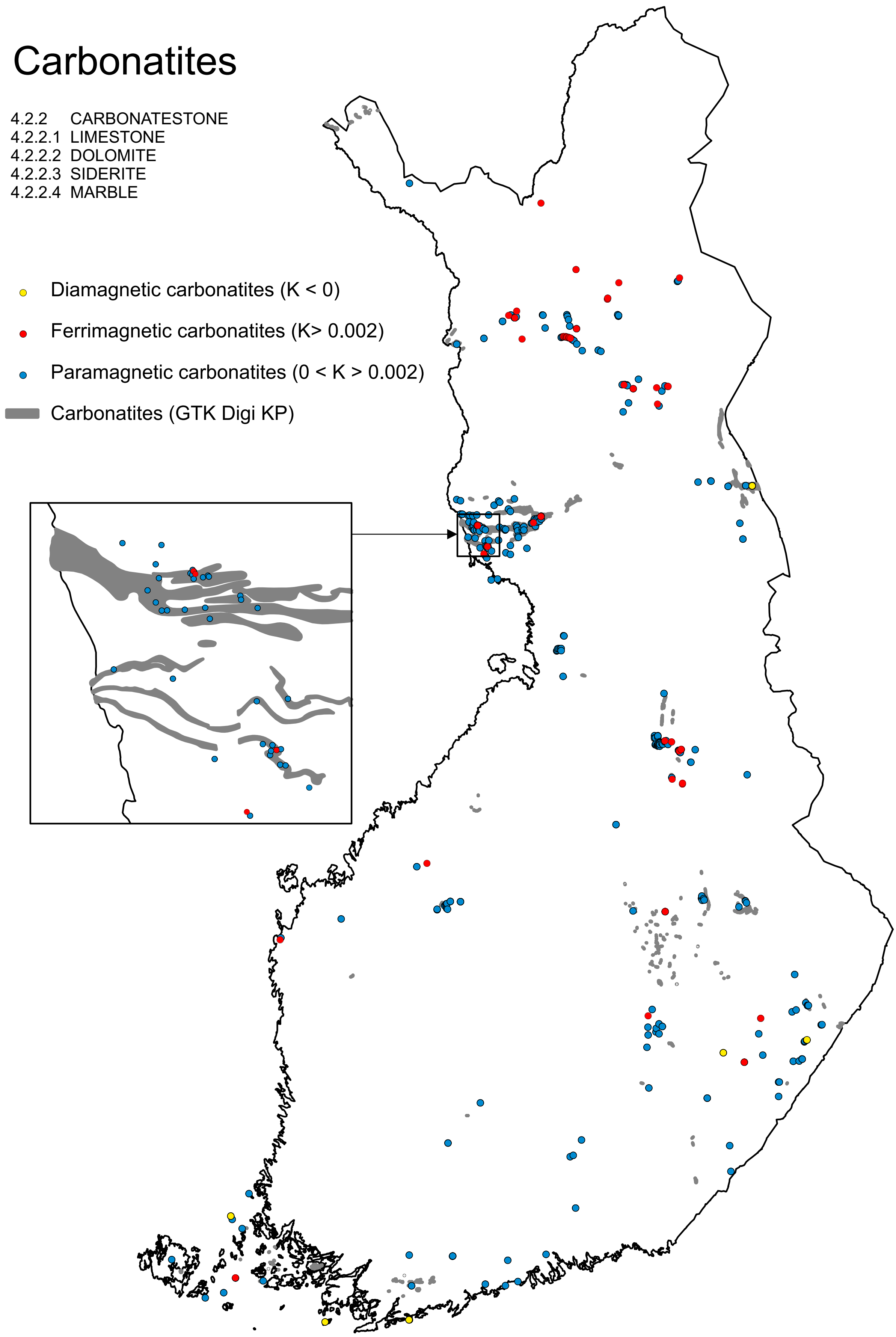


Fig. 14. Carbonatites and carbonate sedimentary rock samples. Grey areas show the distribution of carbonatites or carbonate sedimentary rocks in the digital map database. Where the locality is the same, the ferrimagnetic samples are shown on top of the paramagnetic ones, and diamagnetic samples on top of all others.

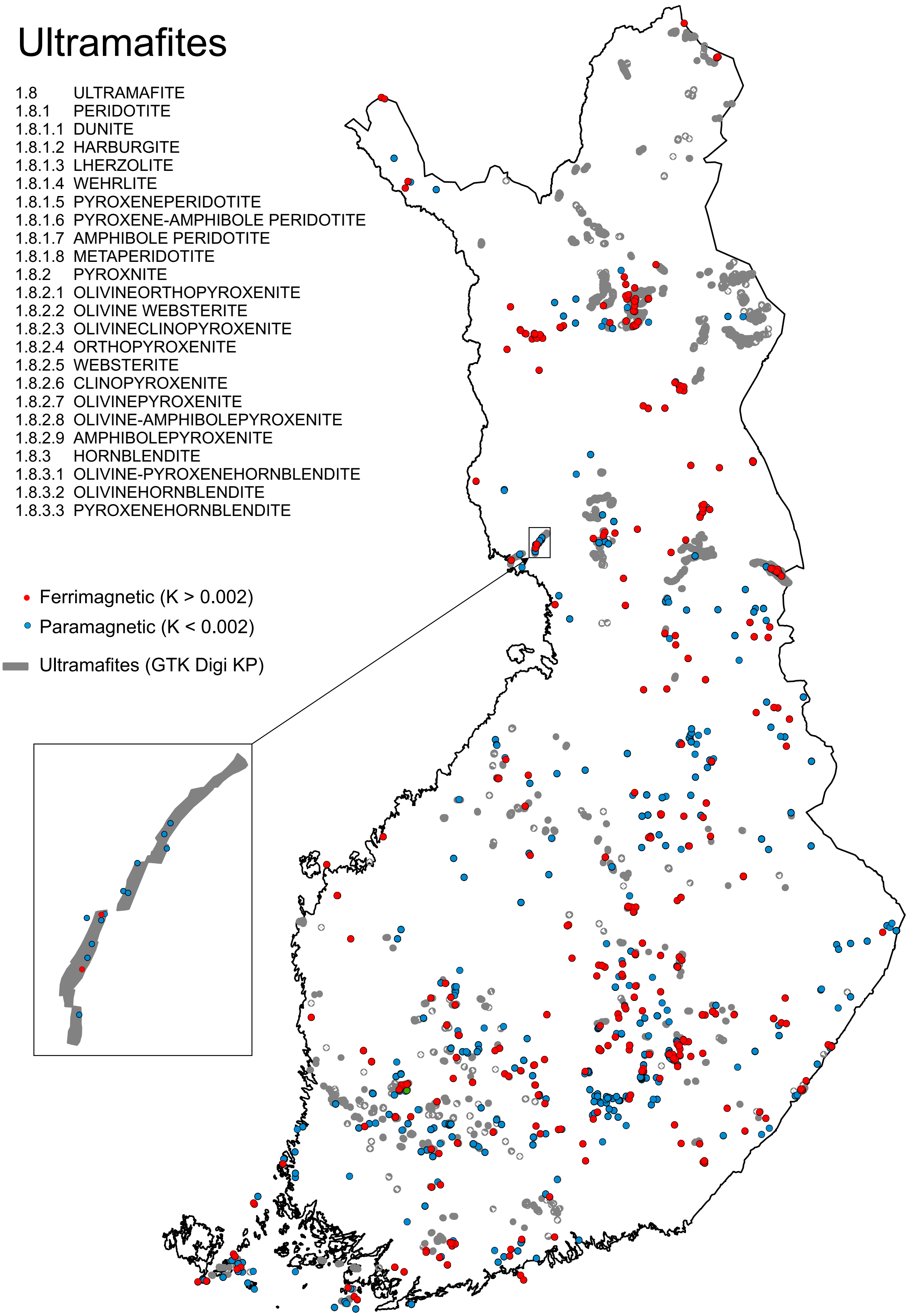


Fig. 15. Ultramafic rock samples. Grey areas show the distribution of ultramafic rocks in the digital map database. Green dots denote paramagnetic and red dots ferrimagnetic petrophysical samples. Where the locality is the same, the paramagnetic samples are shown on top of the ferrimagnetic ones.

5 GEOLOGICAL APPLICATIONS

The physical properties of rocks are controlled by their mineralogy. Consequently, minerals that make up the majority of rocks have a strong influence on their density and magnetic susceptibility. Minerals that are commonly associated with ore deposits, such as pyrite, pyrrhotite or magnetite, have petrophysical properties that differ greatly from the properties of the rock-forming minerals. Chemical alteration produces alteration minerals whose physical properties may also differ considerably from the properties of the original rock. However, because chemical alteration does not result in a completely altered rock, many rocks contain a mixture of primary and secondary minerals whose relative proportions influence the physical properties. Due to the wide variability in mineralogy causes, no rock has a single definitive set of petrophysical properties. Therefore, when plotted on a graph of density and magnetic susceptibility, the variability in properties can be described as a limited field or a cluster of samples. Samples plotted outside this field may be expected to show altered mineralogy.

In the following, the first example displays plotted graphs of the density and magnetic properties of two rock types containing either magnetite or pyrrhotite as their main magnetic mineral. The second example compares the typical properties of different magnetite or pyrrhotite bearing samples from mineralized regions. The third example shows how hydrothermal alteration affects the physical properties of greenstones.

5.1 Rock types: magnetite or pyrrhotite as the main magnetic mineral

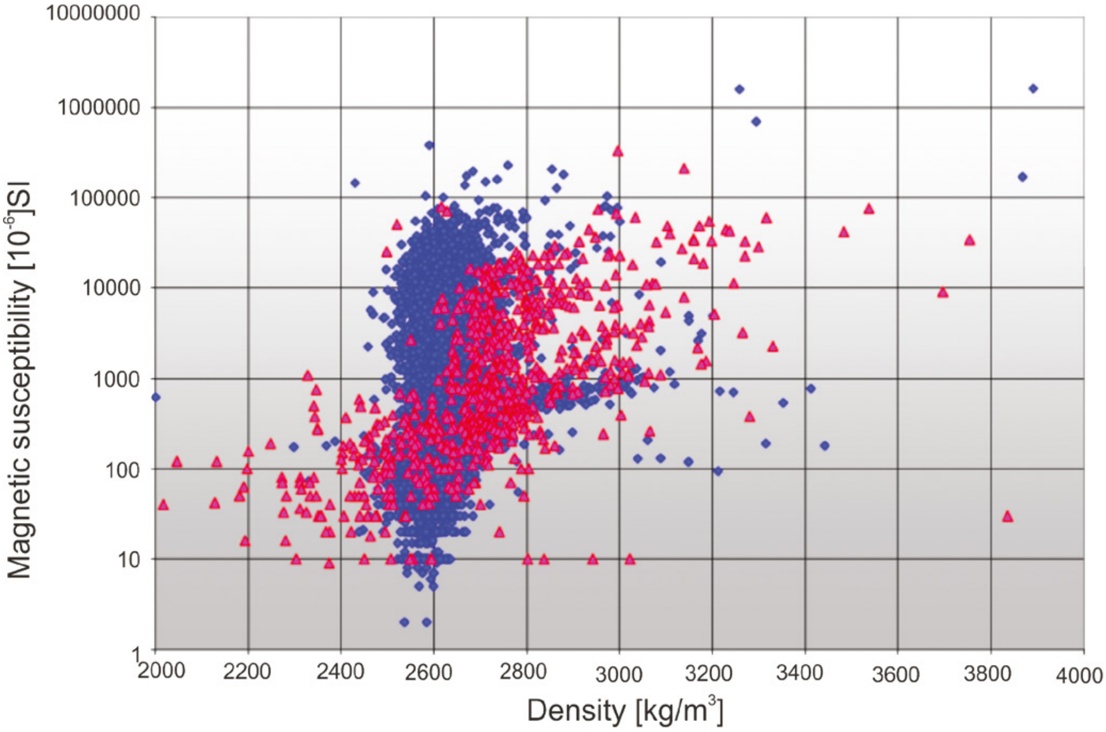
Variability in the petrophysical parameters of two rock types having either magnetite or pyrrhotite as their main magnetic mineral are compared by plotted graphs of density, susceptibility and the Q-ratio. Granites can be regarded as typical magnetite-bearing rocks, and they are represented by >7400 samples. Metamorphosed graphite-bearing shales (black schists) commonly contain monoclinic pyrrhotite as their main magnetic mineral, and they are represented by >700 samples in the data collection. These two rock types occupy completely different fields in the plots (Fig. 16), with black shales occupying the “high density - high remanence” field and granites the “high susceptibility - low remanence” field. Samples with susceptibilities of <0.002 (SI) can be practically regarded as not containing ferrimagnetic pyrrhotite.

Granites (in blue)
- Wide susceptibility range up to 1 (SI units);
- Densities mainly from 2500 to 2700 kg/m^3;
- Q-ratios typically <5 for samples that carry ferrimagnetic minerals (k > 0.002 SI).

Graphite-bearing schists (in red)
- Wide variability in susceptibilities, almost linear susceptibility/density distribution;
- Wide density variation, depending on the con-tent of graphite (low density) and sulphides (high density);
- Wide range of Q-ratios, from 10 to 1000 for samples with k > 0.002 SI.

5.2 Ore deposit types: magnetite, pyrrhotite or grain-size effect

Mineralization may produce petrophysical properties that differ from the properties of the rock that hosts mineralization. Distributions of density, magnetic susceptibility and the Q-ratio for samples containing either magnetite or pyrrhotite show clustering of samples depending on their magnetic mineralogy (Fig. 17, see explanation of symbols in Table 3). The petrophysical properties of ore samples differ extensively from the same properties of serpentinized, magnetite-bearing but non-ore samples from the Outokumpu drill core or from ordinary black shales containing ferrimagnetic pyrrhotite. Magnetite-bearing ore samples, even if slightly altered, possess the highest density and susceptibility values (Fig. 17a). Those samples containing fine-grained magnetite and ferrimagnetic pyrrhotite (IOCG-type mineralization) have susceptibilities otherwise similar to ordinary black shales, but their Q-ratios are orders of magnitude greater, from several tens to several hundreds (see a)



b)

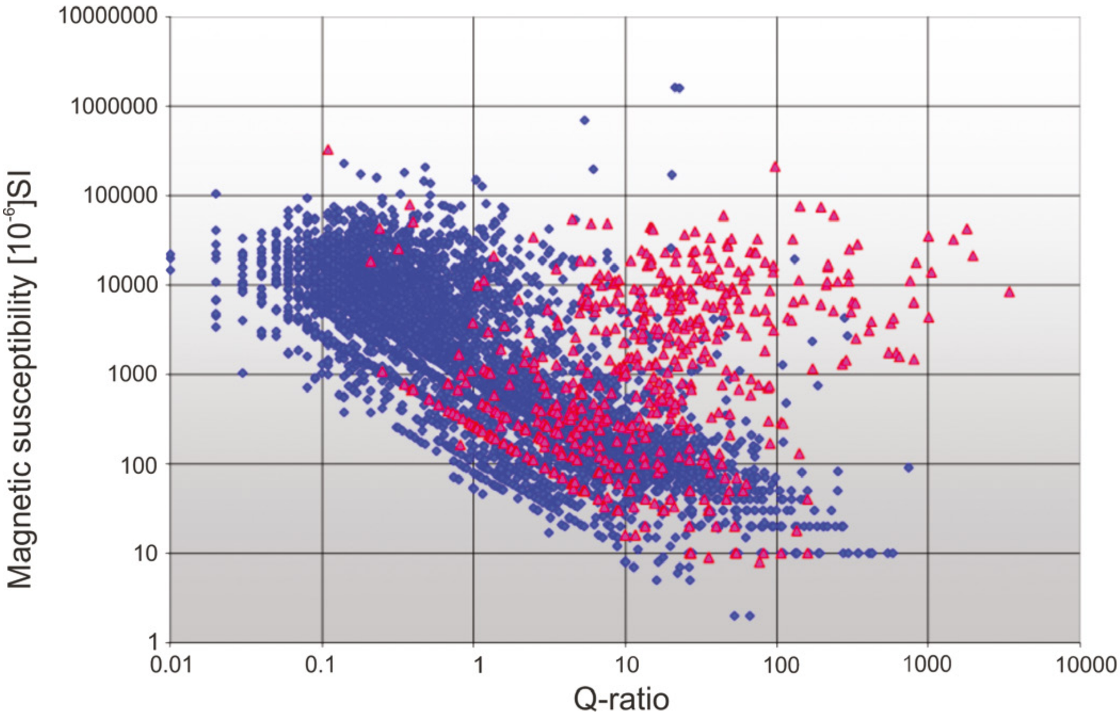
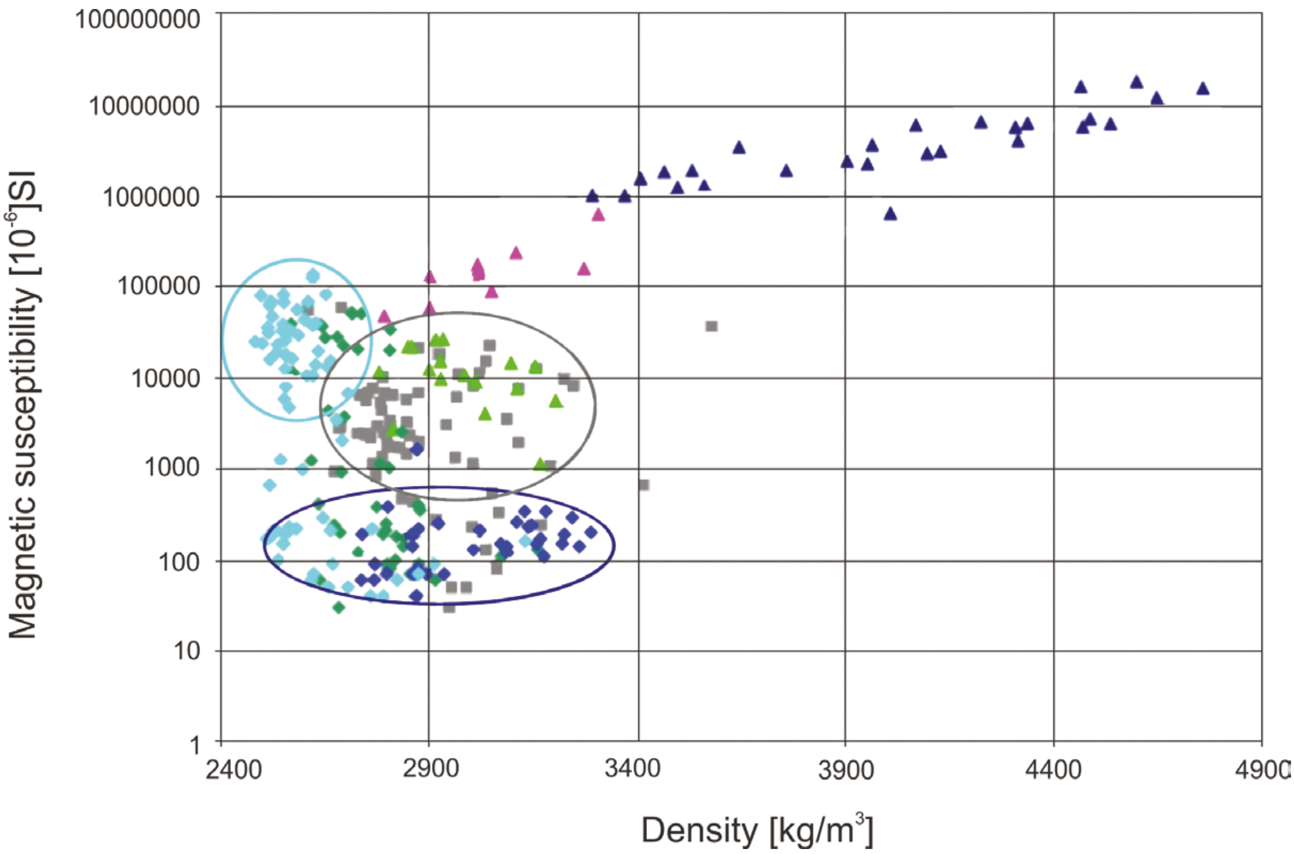


Fig. 16. Comparison of petrophysical distributions for granites (in blue) and black schists (in red): a) susceptibility vs. density, b) susceptibility vs. Q-ratio. Granites > 7400 samples; graphite-bearing schists > 700 samples.

a)



b)

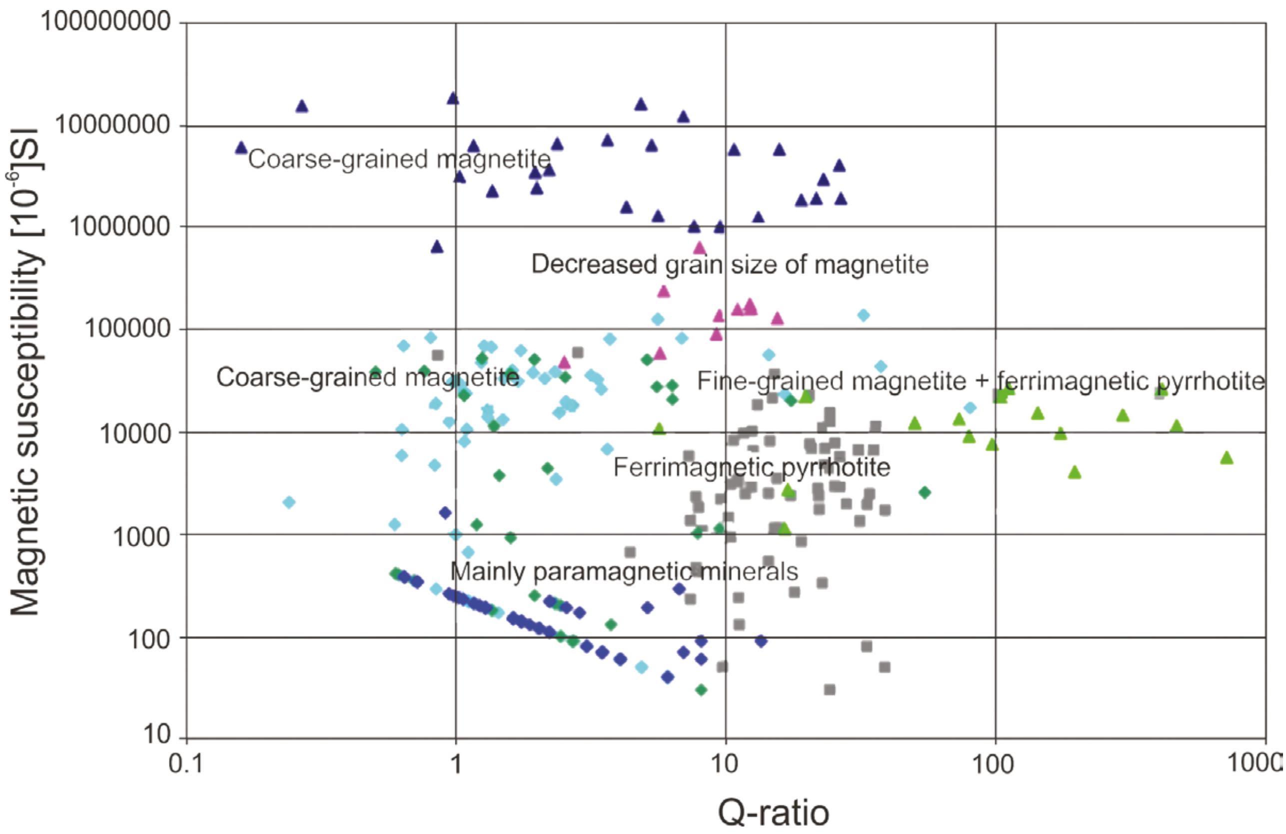


Fig. 17. Comparison of petrophysical distributions for samples representing varying magnetic mineralogy: a) susceptibility vs. density, b) susceptibility vs. Q-ratio. The samples are from the petrophysical data collection and from the Outokumpu Deep Drill Core (Airo et al. 2011a). See explanation of sample symbols in Table 3.

Table 3. Petrophysical parameters vs. magnetic grain size.

Type of sample	Symbol	Magnetic grain size	Density kg/m^3	Magnetic susceptibility (SI units)	Q-ratio
Magnetite-bearing ore deposit samples	▲	From coarse to decreased	3400–3900	10–100	0.1–12
Magnetite ore, slightly altered	▲	Decreased	2900–3400	0.1–1	~10
Magnetite + pyrrhotite	▲	Fine-grained magnetite + monoclinic pyrrhotite	2800–3200	0.0001–0.01	10–1000
Black schists, ordinary and mineralized	■	Monoclinic pyrrhotite	2700–3100	< 0.0001–1	10–50
Outokumpu Deep Drill Core: skarn	◆	No ferromagnetism	2800–3300	< 0.0001	No meaning
Outokumpu Deep Drill Core: serpentine rocks	◆	From coarse to decreased	2600–2900	0.00001–0.1	1–10
Outokumpu Deep Drill Core: serpentinite	◆	Coarse	2500–2900	0.00001–0.1	1–15

difference in Fig. 17b). The densities of serpentinite samples are low, as expected, but their magnetic properties vary from weak to high, depending on the degree of alteration. The low Q-ratios of ~1 indicate a coarse grain size of magnetite, as is typical for serpentinized mafic/ultramafic rocks (see Airo et al. 2011a for a more detailed explanation of the petrophysical properties of the Outokumpu Deep Drill Core). In a broad sense, low Q-ratios of <1 indicate coarse-grained magnetite, while Q-ratios of >10 are related to samples containing ferrimagnetic monoclinic pyrrhotite or fine-grained magnetite. This type of comparison can be used to give an initial estimation of the magnetic mineral type and grain size for sample sets with previously unknown magnetic mineralogy.

5.3 Effect of chemical alteration

Chemical alteration means a change in the original mineralogy of a rock, which in turn results in a change in the petrophysical properties. The effect of hydrothermal alteration on magnetic mineralogy was studied in mafic to ultramafic volcanic rocks from the Kittilä (Central Lapland) greenstone belt (Airo 2007, also Airo & Mertanen 2008). Post-orogenic gold mineralization is known to be related to ultramafic rocks that were affected by potassic alteration. In the alteration processes, magnetite was proportionally destroyed, resulting in reduced magnetization of the ultramafic rocks. A series of altered samples was measured for their density, magnetic susceptibility and remanent magnetization. Their susceptibility vs. density diagram in Figure 18 shows the overall petrophysical trend of a decreasing susceptibility and an increasing density related to an increasing degree of alteration. The iron released from the destruction of magnetite is incorporated with Fe,Mg -carbonates, which have a high density but a low magnetic susceptibility. Q-ratios tend to grow with a decreasing grain size of magnetite. Strongly altered samples do not contain any (or very little) magnetite, as indicated by their susceptibilities being of the same value as paramagnetic silicates.

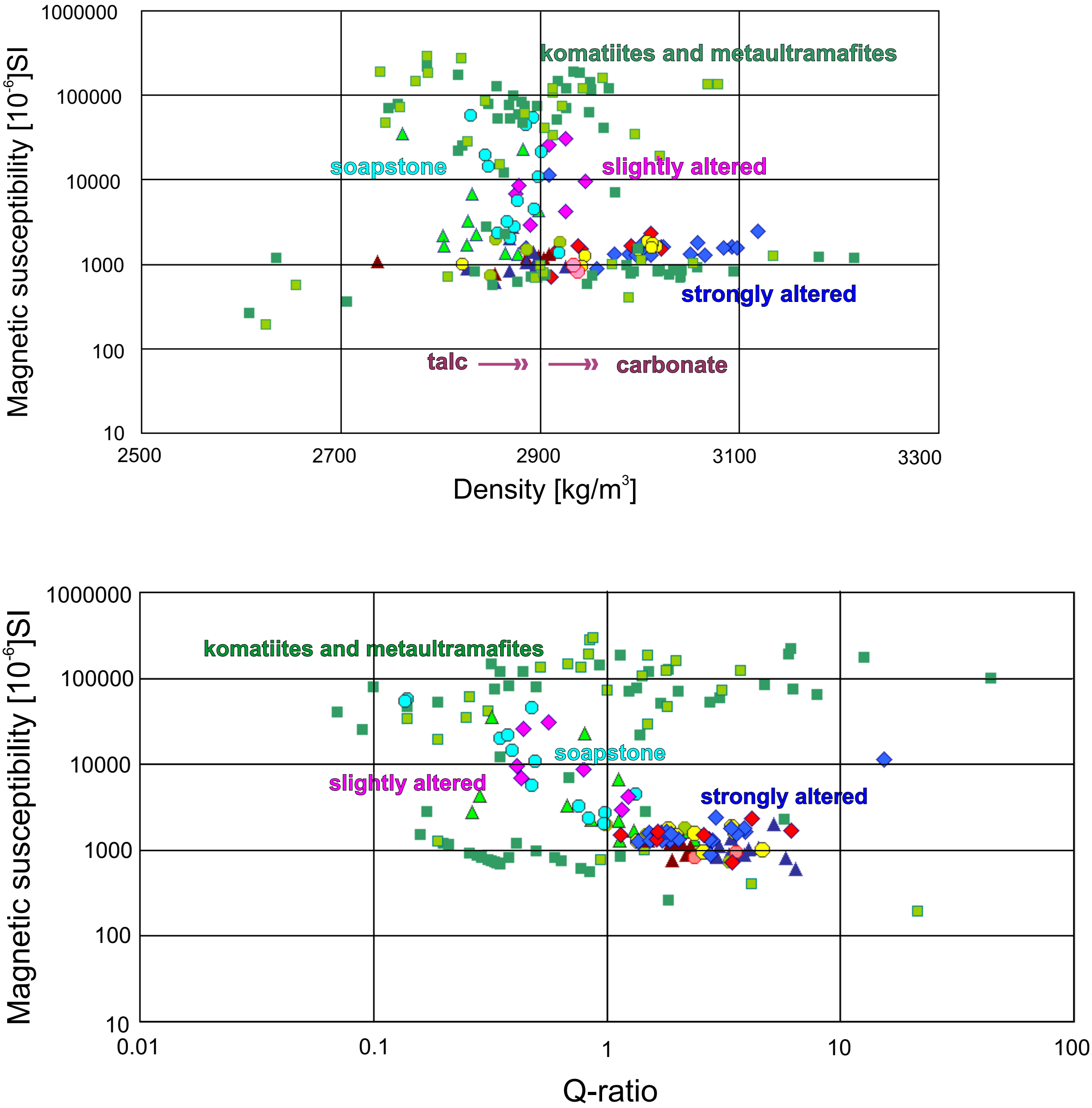


Fig. 18. Effect of chemical alteration on the density and magnetic properties of ultramafic Au-prospective samples from the Kittilä (Central Lapland) greenstone belt in northern Finland (Airo 2007).

6 SUMMARY

Investigations of petrophysical properties, their variability and dependences can facilitate the understanding of the relationship between geophysics and geology. Management of rock physical data and their measurement has been a long-term project of GTK, with the result that GTK can now provide one of the largest collections of petrophysical rock types in the world. The foundation for this work was that in parallel with the development of an airborne geophysical survey programme, GTK decided to establish and develop a petrophysical laboratory. Equipment was designed for the rapid measurement of a large number of samples with sufficient accuracy for the needs of interpreting airborne geophysical data. This development now enables petrophysical studies and summaries to be used to characterize different rock types and ore deposits to help the understanding of their mineralogical and geochemical variability. In geophysical inversion, petrophysical data can provide information for more reliable geological models and can be used to separate outcropping shallow or deep anomaly sources.

This report characterizes petrophysically different rock types in Finland and complements the previous summaries that have been presented in the course of data collection. The average petrophysical properties representing different rocks types are consistent with those given in the worldwide literature and as calculated theoretically (e.g., Clark 1997, Hrouda et al. 2009). The general conclusion from the datasets introduced in this report is that the densities of rock types closely depend on the rock-forming minerals, and that all rock types show wide variability in their magnetic properties, commonly grouping into two to three magnetic categories. The magnetic variations reflect the ferrimagnetic mineral content of rocks, and the Q-ratios for ordinary silicate rocks may unexpectedly be as high as above 10, which emphasizes the dominance of remanent magnetization.

The wide coverage of petrophysical samples with information on their sampling site can be utilized in regional GIS-based statistical investigations and for preparing petrophysical maps of density and magnetic susceptibility. However, the petrophysical properties vary greatly, even over a short distance, and petrophysical information consists of point data with irregular sampling. Therefore, a petrophysical measurement can only be used to estimate the anomalous source rock and its properties at the sampling site. This information can be generalized more widely by presuming that the intensity and pattern for the geophysical anomaly are homogeneous for a particular geological unit. As shown by Pirttijärvi et al. (2011), data interpolation and extrapolation over large areas without any sample points can give misleading mapping results. In geoscientific classifications, such as SOM analysis, petrophysical point data can only be compared with regional geophysical grids with caution.

ACKNOWLEDGEMENTS

The importance of the petrophysical database lies in the systematic, careful sample and data handling throughout the history of the GTK petrophysical laboratory. All those involved with sample preparation, measurement procedures and data management are here acknowledged. We thank Dr Satu Mertanen and Dr Markku Pirttijärvi for their constructive advice to improve the text and Roy Siddall for checking the English.

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Bedrock samples for petrophysical laboratory measurement have been collected in Finland from the 1970s, since the design of an in-house petrophysical laboratory was begun at GTK. The petrophysical equipment was initially designed for rapid determination of the density and magnetic properties of hand samples with a reasonable accuracy and without time-consuming preparation. This method quickly provided background data for the interpretation of country-wide airborne geophysical surveys. The number of rock samples has gradually grown on a yearly basis and now covers the whole of Finland in an irregular net.

Throughout the years, the measurement results have been stored in a petrophysical register, which by the end of the 1990s included more than 130,000 samples. This collection contains information on the density, magnetic susceptibility and intensity of remanent magnetization for different rock types. Because these petrophysical properties of rocks mainly depend on the mineralogy of the rock and the concentration of accessory magnetic minerals, the information can be used to geophysically characterize different rock types of the Finnish Precambrian bedrock.

We present summaries on density, magnetic susceptibility and remanent magnetization, and include the calculated Koenigsberger ratio (Q) plus the induced and total magnetization for the most common rock types in Finland. We also include an explanation of the sampling procedure and measurement philosophy. In addition to geological mapping and mineral exploration, petrophysical properties of rocks have applications in land use, construction rock material and environmental studies. This report serves as a concise user guide to petrophysical data.

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