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Edited by Pentti Hölttä

GEOLOGIAN TUTKIMUSKESKUS **GEOLOGICAL SURVEY OF FINLAND**

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The Geological Survey of Finland (GTK) aims to be an internationally recognized authority in research themes related to mineral resources and raw materials supply. Within GTK the Mineral Potential research programme is tasked with identifying commercially significant mineral deposits and prospective terrains in order to secure future raw material supplies for the mining and mineral extraction industries.

The Mineral Potential research programme is wide in scope and multidisciplinary in nature and for this reason it was considered necessary to provide overviews of current research activities, for promoting awareness both within GTK and within the community and stakeholders at large. This was also a response to requests to improve networking between units, disciplines, and old and young, lay foundations for new ideas and innovations, and develop scientific knowledge and skills. The three day Mineral Potential Workshop was planned to fulfill all these needs. The workshop was held at Hotel Rauhanlahti, Kuopio from 8–10.5.2012 and the abstracts of the presentations and posters are published here in this GTK Report of Investigation volume. The organizing committee included Pentti Hölttä, Asko Kontinen, Raimo Lahtinen, Tero Niiranen and Heikki Salmirinne. Asko Kontinen and Anneli Hukkanen were responsible for practicalities, Pentti Hölttä edited the volume and Peter Sorjonen-Ward proofread the language.

Altogether 59 scientists participated, and 44 oral and 12 poster presentations were given in nine sessions. The workshop was opened by Asko Kontinen followed by introductions to "Mineral resources and raw materials supply impact area" by Pekka Nurmi and the Eco-efficient mining research programme by Tommi Kauppila. The first day then continued with four sessions; "Mineral raw-materials, material flows and data models", "Bedrock geology research I and II" and "Isotope geology and mineralogy". Many of the studies presented in three later sessions utilized the age data produced by the new LA-MC-ICPMS laboratory at Otaniemi. Results of mapping projects at different scales, from national (1:1 million map) via regional scale (metamorphic studies in Pohjanmaa, geology of the Kuopio district) to more detailed studies on different types of alkaline granite suites were also shown.

In the Wednesday morning we visited Siilinjärvi apatite mine and the nearby, newly exposed, Saarinen quarry. Mineralogy and rock units of this unique Archean carbonatite were studied under the guidance of Mine Geologist Pasi Heino (Yara). In the afternoon we had two sessions in "Ore geology research" with presentations varying from Ni-Cu-PGE deposits in mafic rocks via the unique Talvivaara deposit to lithium deposits in pegmatites. Regional potential evaluation studies were also presented. The session "Numeric and visual modeling, GIS-analysis I" comprised two oral talks on 3D modeling and one on numerical simulations.

The session "Numeric and visual modeling, GIS-analysis II" started the Thursday morning with four presentations on different methods, with case studies that can used as exploration tools. This session was followed by a large session on "Exploration methods" with several case studies using geophysical and geochemical methods, and also a biogeochemical approach, analyzing juniper and spruce. During the afternoon we had first presentation about reflections from the "young scientists" and then general discussion about the future need and contents of this type of meeting. The general agreement was that these workshops are useful and hoped-for; they should be biennial and continuous development to improve both scientific skills and social interaction is considered necessary.

In conclusion, there is clearly a need within GTK for internal scientific meetings like the Mineral Potential Workshop. Most of the presentations were of high quality and were well presented, and also in many cases showed novel ideas and data. The goal of the meeting was to fulfill the GTK needs in in-house knowledge transfer, networking and creating new research ideas. In addition, the days gave a very good cross-section of the current research done in the Mineral Potential research programme at GTK.

Raimo Lahtinen

Keywords (Georef Thesaurus, AGI): economic geology, potential deposits, symposia, Finland

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GTK:n tavoitteena on tulla kansainvälisesti merkittäväksi vaikuttajaksi mineraalivarantojen ja niiden kestävän kehityksen tutkimuksessa. GTK:n mineraalipotentiaalin tutkimusohjelman tavoitteena on kaupallisesti merkittävien mineraaliesiintymien ja lupaavien alueiden tunnistaminen, jotta kaivos- ja mineraaliteollisuuden raaka-ainetuotanto voidaan varmistaa tulevaisuudessa.

Mineraalipotentiaalin tutkimusohjelma on laaja-alainen ja monitieteellinen. Tämän vuoksi katsottiin tarpeelliseksi tuottaa nykyisistä tutkimustoimista katsaus, jolla voidaan lisätä sekä GTK:n että yhteisön ja sidosryhmän tietoisuutta. GTK:lle on myös esitetty useita pyyntöjä parantaa yksiköiden ja alojen sekä vanhojen ja nuorten verkostoitumista, luoda perusta uusille ideoille ja innovaatioille sekä kehittää tieteellisiä tietoja ja taitoja. Kolme päivää kestävä mineraalipotentiaalityöpaja suunniteltiin vastaamaan näihin tarpeisiin. Työpaja pidettiin Hotelli Rauhalahdessa Kuopiossa 8.–10.5.2012 ja esitelmien lyhennelmät ja posterit julkaistaan tässä GTK:n tutkimusraportissa. Järjestelytoimikuntaan kuuluivat Pentti Hölttä, Asko Kontinen, Raimo Lahtinen, Tero Niiranen ja Heikki Salmirinne. Asko Kontinen ja Anneli Hukkanen vastasivat käytännön asioista, Pentti Hölttä toimitti julkaisun ja Peter Sorjonen-Ward tarkasti tekstien englannin kielen.

Työpajaan osallistui yhteensä 59 tutkijaa, ja yhdeksän session aikana pidettiin 44 suullista esitystä ja 12 posteriesitelmää. Työpajan avasi Asko Kontinen, ja avausta seurasi Pekka Nurmen johdanto ”Mineraaliresurssien ja raaka-ainetuotannon vaikutusalueet” ja Tommi Kauppilan ”Ympäristötehokas kaivostutkimusohjelma”. Tämän jälkeen ensimmäinen päivä jatkui neljällä sessiolla, jotka olivat ”Mineraaliraaka-aineet, raaka-ainevirrat ja tietomallit”, ”Kallioperägeologian tutkimus I ja II” ja ”Isotooppigeologia ja mineralogia”. Useissa kolmessa jälkimmäisessä sessiossa esitetyissä tutkimuksissa oli käytetty GTK:n uudessa LA-MC-ICPMS-laboratoriossa tuotettuja ikätietoja. Sessioiden aikana esiteltiin myös kartoitusprojektien tuloksia valtakunnallisen (1:1 000 000) ja alueellisen tason kartoista (Pohjanmaan metamorfiset tutkimukset, Kuopion alueen geologia) erityyppisiä alkaligraniittisarjoja koskeviin yksityiskohtaisempiin tutkimuksiin.

Keskiviikkoaamuna vierailimme Siilinjärven apatiittikaivoksessa ja läheisellä uudelleen avatulla Saarisen louhoksella. Tämän ainutlaatuisen arkeeisen karbonatiitin mineralogiaa ja kivilajiyksiköitä tutkittiin Yara Suomi Oy:n kaivosgeologin Pasi Heinon opastuksella. Iltapäivällä oli kaksi malmigeologian tutkimusta käsittelevää sessiota, joiden esitelmät käsittelivät mafisten kivien nikkeli-kupari-platinametalliesiintymiä, ainutlaatuista Talvivaaran esiintymää ja pegmatiittien litiumesiintymiä. Sessioissa esiteltiin myös alueellisia potentiaaliarvioita. Sessio ”Numeerinen ja visuaalinen mallinnus, GIS-analyysi I” sisälsi kaksi suullista esitelmää 3D-mallinnuksesta ja yhden esitelmän numeerisesta simulaatiosta.

Sessio ”Numeerinen ja visuaalinen mallinnus, GIS-analyysi II” alkoi torstaiaamuna neljällä esitelmällä eri menetelmistä. Ne sisälsivät esimerkkitutkimuksia, joita voidaan käyttää tutkimustyökaluina. Tätä sessiota seurasi laaja malminetsintämenetelmiä käsittelevä sessio, jossa esiteltiin esimerkkitapauksia geofysikaalisista ja geokemiallisista menetelmistä sekä biogeokemiallinen menetelmä, jolla analysoitiin katajia ja kuusia. Iltapäivän aikana kuultiin ensimmäinen ”nuorten tutkijoiden” esitelmä heijastusluotauksista, ja tämän jälkeen keskusteltiin yleisesti tämäntyyppisten kokoontumisten tarpeellisuudesta tulevaisuudessa ja mahdollisesta sisällöstä. Yleinen mielipide oli, että tällaiset työpajat ovat hyödyllisiä ja toivottuja, ja niitä tulisi järjestää kahden vuoden välein. Jatkuva kehittyminen tieteellisten taitojen ja sosiaalisen kanssakäymisen parantamiseksi katsottiin välttämättömäksi.

GTK:ssa on selkeä tarve mineraalipotentiaalityöpajan kaltaisille sisäisille tieteellisille kokouksille. Useimmat esitelmät olivat korkeatasoisia ja hyvin toteutettuja, ja monissa niistä esiteltiin myös uusia ideoita ja tietoja. Kokoontumisen tavoitteena oli täyttää GTK:n sisäisen tiedonsiirron, verkostoitumisen ja uusien tutkimusideoiden kehittämisen tarve. Lisäksi näiden päivien aikana nähtiin hyvä poikkileikkaus GTK:n mineraalipotentiaaliohjelmassa tehtävästä tutkimuksesta.

Raimo Lahtinen

Asiasanat (Geosanasto, GTK): malmigeologia, potentiaaliset esiintymät, symposiot, Suomi

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DEVELOPMENT OF A SEMI-AUTOMATED PROCESS FOR INTERPRETATION OF LITHOGEOCHEMICAL BEDROCK DATA USING GEOGRAPHIC OBJECT-BASED IMAGE ANALYSIS (GEOBIA) TECHNIQUES

by

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The volume of geochemical data generated during geological, exploration and environmental mapping programs, is growing rapidly, in part due to advances in the range and quality of chemical analytical techniques and instrumentation, and in part due to increased computational capacity and efficiency in managing and delivering complex, spatially-oriented geochemical datasets.

Object-based image analysis (OBIA) is a concept that facilitates the simultaneous interpretation of large amounts of image-oriented data e.g. dense image data at different scales, object height information and other types of thematic data. It represents a promising approach to optimizing workflows where manual input and processing may inhibit efficient analysis and interpretation of voluminous and multivariate image and feature data.

Recent applications of OBIA to remote sensing have included integrated analysis of geographically bound raster domain imagery and vector domain feature data; this has now developed into a new research field known as Geographic Object-Based Image Analysis (GEOBIA). In this study, GEOBIA concepts and techniques have been combined with GIS spatial analytical tools to develop a more efficient, semi-automated image interpretation process using randomly sampled, lithogeochemical vector domain data. Emphasis was also given to developing an expert-driven data reduction procedure for accurately classifying probable source rock types based on as little geochemical data as possible.

The software used for geographic object-based image analysis, classification and identification in this study were ESRI® ArcGIS™ (ArcGIS) and Trimble© eCognition Developer™ (eCognition). ArcGIS was used for preprocessing and interpolation of GIS point data to raster image sets for the GEOBIA modeling process. eCognition was used for object-based image segmentation of the original raster data, classification of image-based objects with a pattern recognition algorithm and export of vectorized object data for further use in the GIS environment. The resultant classified vector data sets were visualized in ArcGIS and exported as map image products.

The original input data used in this study were derived from the Rock Geochemical Database of Finland (RGDB) compiled, and comprehensively documented by Rasilainen et al. (2007, 2008). This dataset was chosen because it contains analytically consistent and well-documented lithogeochemical data representing a wide range of Finnish bedrock lithologies, as described. The RGDB results were stored in vector format in a GIS database containing bedrock analytical data; for this study, the whole-rock XRF data were used.

The original XRF data matrix in the RGDB had dimensions of 6544 rows by 36 columns. For the purposes of modeling, the data were reduced to four major element oxide components, namely aluminium (Al_2O_3), potassium (K_2O), silicon (SiO_2) and magnesium (MgO), resulting in a matrix with dimensions of 6544 by 4. These four oxides were each chosen to correspond to conceptual rock type model domains representing four dominant Finnish rock type categories (Al_2O_3 = aluminous metasediments or schists, K_2O = granitoids, SiO_2 = siliceous metasediments or quartzites and MgO = mafic rocks).

The four lithogeochemical rock type model domains were individually assigned to form four corresponding raster image colour bands in the CMYK colour domain (Al_2O_3 [min, max] > C=cyan [0, 255], K_2O [min,max] > M=magenta [0,255], SiO_2 [min,max] > Y=yellow [0,255] and MgO [min,max] > K=black [0,255]), by interpolating the total element oxide concentrations with ArcGIS Spatial Analyst Tools. The colour selection was defined so as to correspond as closely as possible to the spectral features assigned to various rock types on the traditional Finnish bedrock geological map, notably schists (blue), granitoids (red), quartzites (yellow) and basic rocks (dark hues) to help to make classification decisions and to outline the classification results later in the eCognition software platform.

The classified C, M, Y and K raster image visualizations were combined in ArcGIS to form a single CMYK raster image data set. In eCognition, the CMYK image data set was processed further as three individual RGB color bands R=red [0,255], G= green [0,255] and B= blue [0,255] and segmented to form image objects from pixel data. Image objects were classified according to their naturally occurring spectral features with a sample-based pattern recognition algorithm. The neighboring objects having the same class were then processed by merging to form larger image objects providing a geographical representation of the interpreted chemically equivalent rock type classes.

The interpreted and classified lithogeochemical image object raster features were exported in vector format to ArcGIS for compilation of a geochemical GIS map presentation and for further optimization in the visualization of map products.

The GIS and GEOBIA techniques and tools together form a very promising, powerful and resource efficient way of interpreting large amounts of geochemical data based on the use of only a few image model parameters. At present, there seem to be no obvious technical limitations in the hardware, software, or computational algorithms for ongoing GEOBIA process development.

Future developments towards a more standardized geochemical GEOBIA interpretation process could include optimizing the image colour domain, choosing a more suitable interpolation method for sparse and randomly sampled geochemical GIS data, and finding an efficient image geo-referencing procedure within the overall workflow. The GEOBIA rule sets and procedures developed in this study can also be applied to other types of geochemical data. The integration of geochemical GIS data with other types of geodata in 2D and ultimately in 3D would be another area of potential interest in applying GEOBIA to geological interpretation.

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CLASSIFYING ARCHAEAN GRANITOIDS BASED ON LITHOGEOCHEMICAL DATA WITH SELF-ORGANIZING MAP (SOM) TOOLS

by

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Computational data modeling, making use of pattern recognition algorithms, is being increasingly used alongside conventional statistical analysis in many research applications requiring classification of large and diverse datasets. In recent years, considerable progress has been made in developing software tools enabling rapid data-driven clustering and pattern recognition techniques derived from neural network research, such as Kohonen's self-organizing map (SOM) algorithm (Kohonen 1981, Laaksonen & Honkela 2011). Data-driven analytical approaches are in some respects more objective than more supervised knowledge-driven modeling. The SOM algorithm is therefore ideally suited to data-exploration in the early stages of computational modeling for example in data classification or data reduction decisions, before using expert-driven or supervised learning methods and algorithms.

With ever-increasing amounts of geodata, computational efficiency in interpreting multidimensional datasets is essential, requiring the development of appropriate analytical tools. At the same time, the development of globally standardized geoscience data formats and the compilation of readily accessible global databases are making the use of computational modeling approaches more attractive and feasible.

In this study we used an experimental data-driven classification approach with a commercially available SOM algorithm software application (CSIRO® Self Organizing Maps aka SiroSOM™). Pre-processing of the data also involved computation of theoretical CIPW norms from major element oxide abundances using GCDkit software (Janoušek et al. 2006) version 3.0. After the SOM classification, IBM® SPSS® Statistics Version 20 software was also used for further analysis and visualization of data results. The main aim of the study is to investigate whether some of the expected elemental characteristics of specific geological rock types could be identified from a large lithogeochemical dataset using pattern recognition techniques. Ideally, we should expect to recognize element enrichment or depletion trends through clustering in the SOM output matrix.

Our study made use of an international compilation of Archaean granitoid chemical data described in (Martin & Moyen 2002) and (Moyen 2011), consisting of 2642 bedrock whole-rock analyses, supplemented with additional data from

Finland. The database includes Archaean gneissic and plutonic rocks classified as grey gneisses, TTG orthogneisses, TTG plutons, sanukitoids, quartz diorites, syenites, and potassic granites (leucogranites) and is probably representative of Archaean plutonic rocks in general. However, because the analyses were made in different laboratories, the possibility of systematic or other types of errors needs to be considered when interpreting the data. Likewise we also assume that the effect of alteration processes during or after crystallization may not always be negligible.

The database consisted of whole-rock major element and trace element data, with sampling and analytical techniques and metadata described in the original source publications. Even though sample locations were given, the data was not positioned, and so our analysis is not spatially constrained. Wherever analytical data are missing or uncertain, or where values were below specified detection limits, data were classified as missing values and assigned a value of -99 in the dataset. The geochemical data matrix dimensions of the imputed database for SOM analysis were 2642 rows by 63 columns.

Two experimental datasets were derived from the imputed database: one containing the original major oxide components as well as trace element assay values, and another consisting of calculated CIPW norm mineralogy, together with the original trace element data.

Both of these datasets were then filtered such that those variables that lacked data for more than 50% of cases were excluded from the computation process. Before computation, logarithmic transformations were performed in SiroSOM for all of the filtered data, because the abundances of most chemical compounds and elements, with the exception of SiO_2 and Al_2O_3, did not follow normal distribution. The K-means clustered results from the SiroSOM analysis were exported in a standard spreadsheet format for further statistical evaluation and presentation purposes in other applications, such as SPSS.

The analysis was intended to discriminate compositional differences amongst Archaean granitoids and gneisses and preliminary results reveal a positive correlation between Ni and Cr concentrations for the whole dataset, as expected. A positive correlation between Ni and Cr was also confirmed with respect to some of the calculated normative mineral phases, particularly for mafic compositions, including hypersthene (MgO), hematite (Fe_2O_3) and anorthite (CaO), as well as apatite (P_2O_5), TiO_2-bearing ilmenite, and rutile, though these were more subtle. The SOM visualization also identified some specific rock types that could be distinguished from the main cluster trends (e.g. sanukitoids, syenites, and potassic granites). There were some indications that potassic granites (leucogranites with high normative Q, Or, and Y)) and syenites (with high Ba, Sr, and low normative Q) may define distinct clusters in the SOM analysis. We also identified some features showing clustering that could be related to sanukitoids or quartz diorites (e.g. moderately high Ba, Sr, high Cr, low normative Q).

The results of this study show that the SOM technique is a useful tool for provisional classification and data exploration for Archaean – and in principle, other – granitoids. The SOM approach represents an efficient approach for interpretation of large multi-element geochemical datasets. The SiroSOM application is in general well suited to data reduction and further preparatory analysis and classification of lithogeochemical data. It is also possible to use spatially referenced data in the SOM analysis, allowing visualization of output data in GIS environments where required.

This study demonstrates that the use of SOM together with conventional statistical classification methods is an effective approach in data-driven analysis and interpretation of large geochemical datasets and derivative data, such as normative mineralogy data. There is clearly an increasing demand for such fast and efficient computational techniques when working with large geochemical datasets, in both exploration-oriented and environmental research, for targeting of potential metallogenic anomalies, or contaminant sources has given an extra impetus in applying simple and fast computational modeling methods and tools e.g. in lithogeochemical interpretation. Simultaneous classification of large datasets in a single computational operation can also increase the objectivity of the classification.

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THE LEVIÄKANGAS, SYVÄJÄRVI AND RAPASAARET LITHIUM PEGMATITE DEPOSITS IN THE KAUSTINEN AND KOKKOLA DISTRICTS, WESTERN FINLAND

by

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The 500 km^2 Kaustinen lithium province forms a part of the Svecofennian Pohjanmaa schist belt (Fig. 1). Boulder fans and diamond drilling in the 1960s, 1980s, and 2000s revealed that the Kaustinen region contains dozens of spodumene pegmatite veins. Alviola et al. (2001) suggested that lithium pegmatites in the Kaustinen area belong to the albite-spodumene subgroup of the LCT (Li, Cs, Ta) pegmatite family of Černy and Ercit (2005). Suomen Mineraali Oy conducted the first lithium pegmatite exploration programmes (Boström 1988) in the Kaustinen area in the 1960s, which were followed in the 1980s by Paraisten Kalkki Oy and subsequently, since 1999, by Keliber Oy.

The Geological Survey of Finland (GTK) has been exploring for lithium in the Kaustinen area since 2003. Three deposits have been evaluated and reported to the Ministry of Employment and the Economy, namely Leviäkangas (Ahtola et al. 2010a) and Syväjärvi (Ahtola et al. 2010b) in 2010 and Rapasaaret (Kuusela et al. 2011) in 2012.

These lithium pegmatites are mineralogically similar to each other (Table 1). The average Li_2O (wt-%) concentration varies from 0.74% to 1.18%, which corresponds to the average normative content of 10% to 15% spodumene. Spodumene is the only economic Li-mineral present in the Kaustinen area. It is typically coarse grained and occurs as elongated light grey or green, lath-shaped crystals from 0.5–10 cm in length. The pegmatites are commonly zoned, having higher spodumene concentrations towards the cores of the dykes.

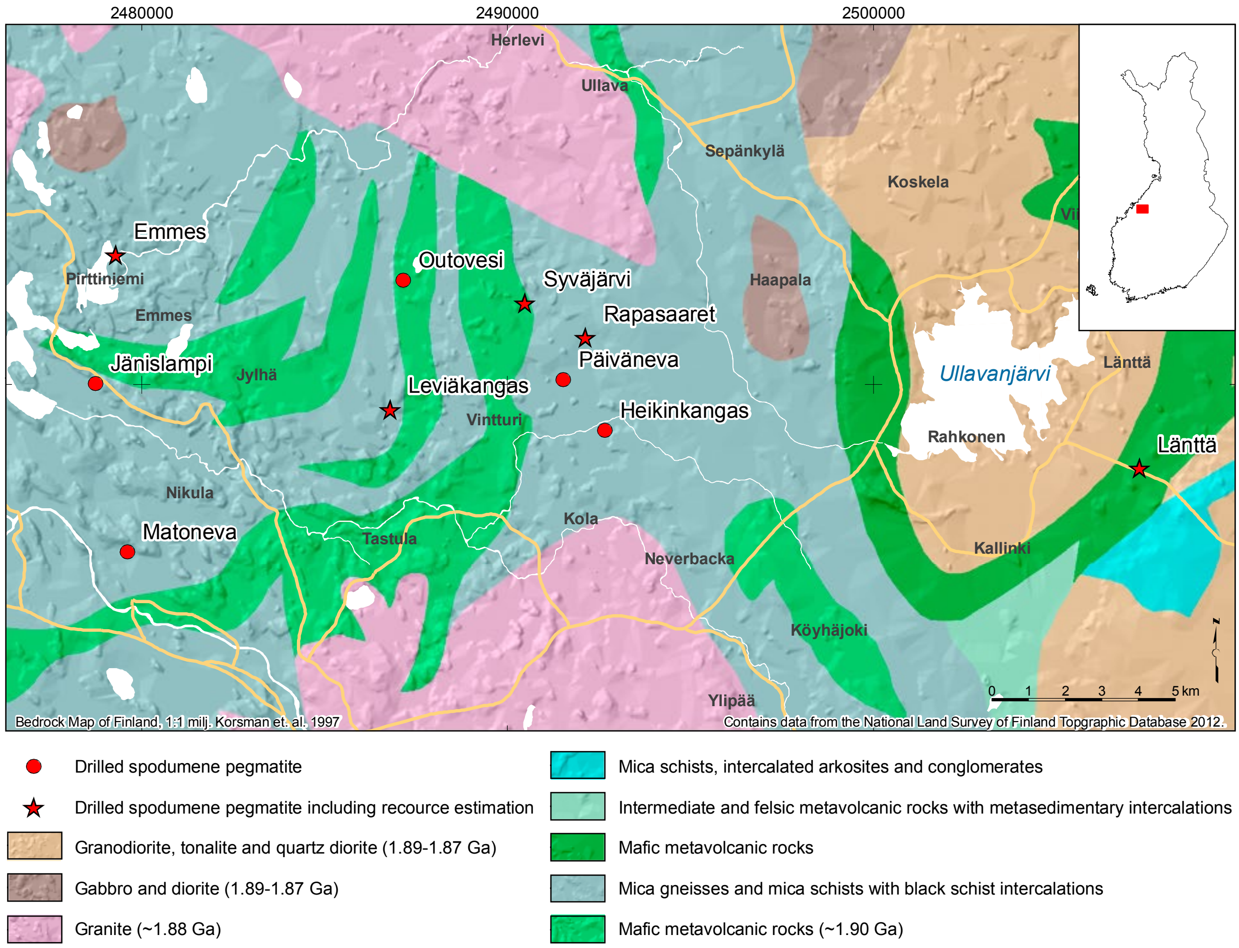

Fig. 1. Regional geological map of the Kaustinen Li province after Korsman et al. (1997), showing the locations of the drilled spodumene pegmatites.

Table 1. Mineral assemblages and the average Li_2O-, Ta_2O_5-, Nb_2O_5- and BeO contents of the Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites.

Deposit	**Main minerals** (in abundance order)	**Accessory minerals**	**Li_2O** %	**Ta_2O_5** ppm	**Nb_2O_5** ppm	**BeO** ppm
Leviäkangas	Albite, Quartz, K-feldspar, Spodumene, Muscovite	apatite, cassiterite, cookeite, garnet, graphite, Mn-Fe phosphate, montebrasite, Nb-Ta oxides, sphalerite, tourmaline, zeolite	0.74	72	87	185
Syväjärvi	Albite, Quartz, K-feldspar, Spodumene, Muscovite	apatite, arsenopyrite, garnet, Nb-Ta oxides, sphalerite, tourmaline	1.00	26	36	148
Rapasaaret	Albite, Quartz, Spodumene, K-feldspar, Muscovite	andalusite, apatite, arsenopyrite, beryl, calcite, chlorite, fluorite, garnet, Mn-Fe phosphates, Nb-Ta oxides, pyrite, pyrrhotite, tourmaline, zinnwaldite	1.18	53	58	502

Lithium resources have been estimated for five deposits in the Kaustinen area (Table 2). Spodumene pegmatites of the Leviäkangas, Syväjärvi and Rapasaaret (total 8.4 Mt) significantly increase the known resources of the Kaustinen region.

Table 2. The known lithium resources of the Kaustinen area.

Deposit	Tonnage (Mt)	Li_2O wt%
Emmes	1.1	1.3
Länttä	2.95	0.92
Leviäkangas	2.1	0.7
Syväjärvi	2.6	0.98
Rapasaaret	3.7	1.02

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REE-RICH ACCESSORY MINERALS IN CARBONATITIC, ALKALINE, APPINITIC AND METASOMATIC-HYDROTHERMAL ROCKS, CENTRAL AND NORTHERN FINLAND

by

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REE-rich accessory minerals from Finnish carbonatitic, alkaline, appinitic, and metasomatic-hydrothermal rocks enriched in REE (Fig. 1) have been studied by electron microprobe. The study revealed spectacularly diverse assemblages of REE - Y -U minerals, exceeding greatly that described previously from carbonatites; the new data provide important insights into the evolution of these late-stage carbonatite –alkaline rocks and the nature of sub-solidus (secondary) alteration processes.

The samples were collected from drill cores and outcrops representing 14 different targets (Fig 1, Table 2). Polished sections from 57 representative samples

Table 1. The main REE-minerals per studied occurrence.

Locality	Rock type	Dominant REE-mineral phases
Jammi	Carbonatite veins	F-apatite, Sr-apatite, monazite, bastnäsite, ancylite, strontianite, baryte
Iivaara	Nepheline-syenite	Apatite, allanite
Otanmäki	Alkaline-gneiss	Fergusonite(Y), Fergusonite(U), allanite, columbite
Korsnäs	Carbonatite	Apatite, monazite, carbocernaite, calcio-ancylite, bastnäsite, baryte, barytocalcite
Uuniniemi	Carbonatite and albitite	Apatite, euxenite, Fe-columbite, Fe-thorite
Mäkärä	Arkosic gneiss	Euxenite, columbite, monazite,zircon
Vanttaus	Appinitic diorite	Apatite, allanite, sphene, zircon
Lehmikari	Appinitic diorite	F-apatite, monazite, allanite, ancylite, thorite, zircon, baryte
Palkiskuru	Albitite	Apatite, bastnäsite, allanite, monazite, ancylite, davidite, masuyite, sayrite, zircon
Palovaara	Albite-carbonate-rock	Allanite; ancylite, bastnäsite and xenotime
Honkilehto	Carbonate mica schist	Bastnäsite, allanite, davidite, U-Pb minerals, U-Si minerals
Kortejärvi	Carbonatite	Apatite, allanite, monazite, bastnäsite, columbite
Laivajoki	Silicocarbonatite	Apatite, monazite, allanite, bastnäsite
Suhuvaara	Appinitic diorite	Monazite, allanite

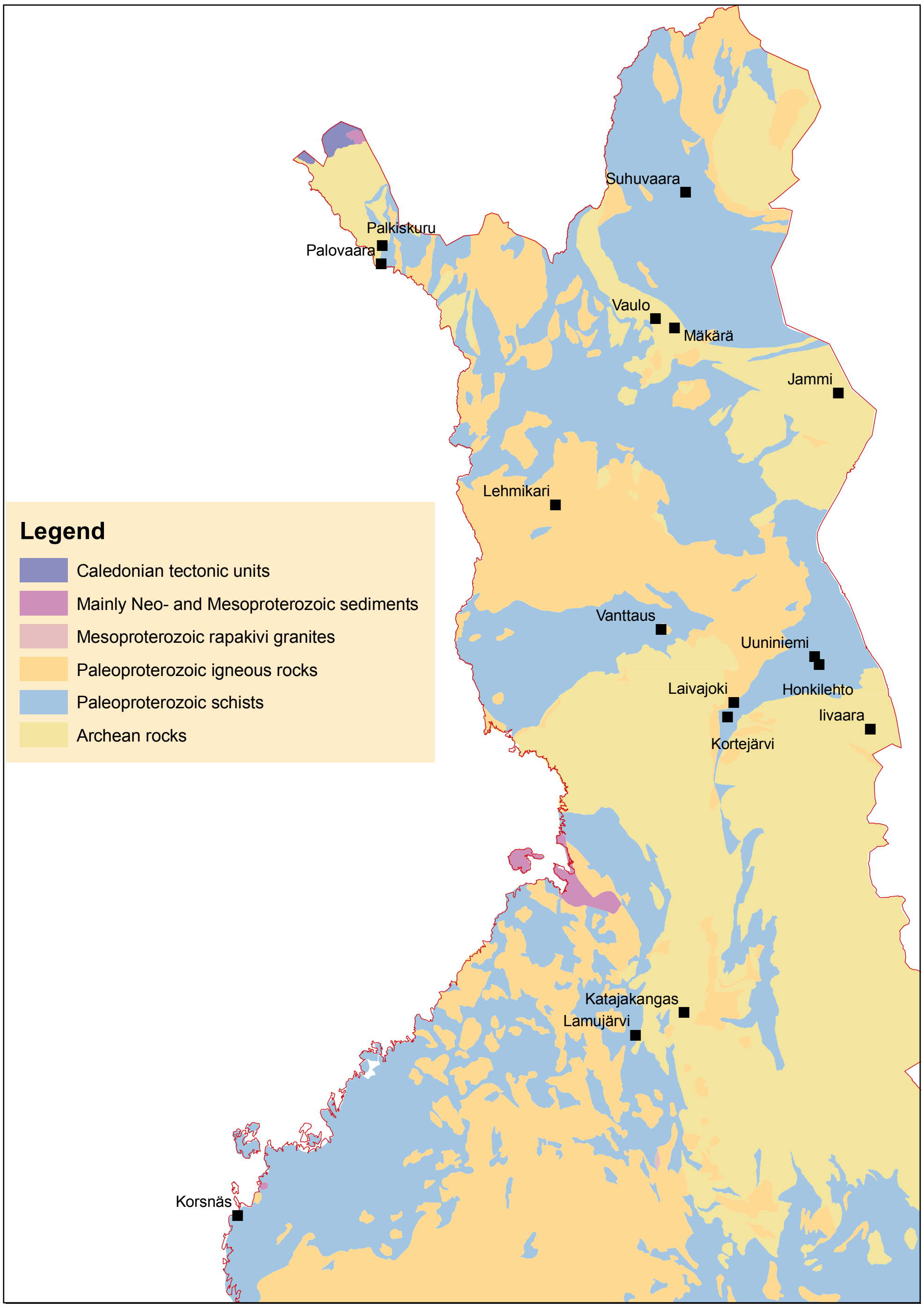

Fig. 1. Location of the studied occurrences of REE enriched rocks.

were prepared and examined first under a polarizing microscope and then by electron microprobe. More than twenty species of REE minerals have been identified and analyzed in detail by the microprobe (EPMA), including monazite-(Ce), bastnäsite-(Ce), ancylite-(Ce), allanite, fergusonite and several U-Pb rich minerals. Results for the selected study targets include:

The Jammi carbonatite veins within the Sokli Fenite zone are characterized by the REE-rich carbonate minerals ancylite and bastnäsite (Fig. 2a). Both these minerals are strongly enriched in LREE, P, F, Sr and Ba. There is also abundant apatite in the Jammi veins, forming large and elongated grains, closely associated with monazite (Fig. 2b).

Allanite-(Ce) and fergusonite (Y) are the most abundant and widespread REE-bearing minerals in the Katajakangas alkali-gneiss at Otanmäki (Fig. 2c). Allanite, which hosts most of the LREE (~50%) and iron Fe_2O_3 (2.5%) is low in aluminium Al_2O_3 (5.9%) as well as in Th (3%) and U.

Important REE-bearing minerals in the calc-silicate gneiss and carbonatite hosted Korsnäs deposit include apatite, monazite, calcio-ancylite and bastnäsite. A characteristic feature of these rocks is the presence of monazite inclusions as isolated anhedral grains or as larger clusters of anhedral grains in large apatite crystals (Fig. 2d).

The Uuniniemi REE-enriched carbonate rocks near Kuusamo are also comprise plentiful apatite with REE-minerals such as monazite (Ce), Fe-columbite, euxenite (Y) and zircon. A representative BSE image of a sample with abundant monazite characterized by large grain size and significant porosity and fractures is shown in Fig. 2 (e, f).

The Mäkärä occurrence in altered arkosic gneisses near Sodankylä is dominated by radioactive minerals such as columbite, monazite and euxenite (Fig. 3a).

Postorogenic appinitic intrusions are widespread within the central Lapland granitoid complex, occurring as numerous small stocks or dikes and also as larger intrusions as at Vanttaus, Lehmikari and Suhuvaara. The appinitic rocks are enriched in P and REE and consequently rich in P and REE-bearing minerals such as allanite and monazite (Fig. 3b).

The REE-enriched albitites at Palkiskuru in Enontekiö contain a wide variety of REE-rich minerals, mainly bastnäsite, monazite, allanite, and xenotime, as well as U-rich minerals such as davidite, masuyite and /or sayrite (Fig. 3c, d).

The sulphide-sericite schists hosting the Honkilehto Au-Co-mineralization in the central part of the Kuusamo belt are also characterized by U-rich minerals associated with bastnäsite and allanite. The Kortejärvi carbonatite in the western part of the Kuusamo belt is characterized by enrichment of apatite with monazite and allanite (Fig. 3e). The nearby Laivajoki carbonatite contains, in addition to carbonate minerals, abundant apatite rich in allanite and monazite inclusions (Fig. 3f).

The results obtained provide a useful reference basis for possible future feasibility studies, as well as important mineralogical insights into the surprisingly varied rock types and mineralizing processes associated with the occurrence of elevated REE in northern Finland.

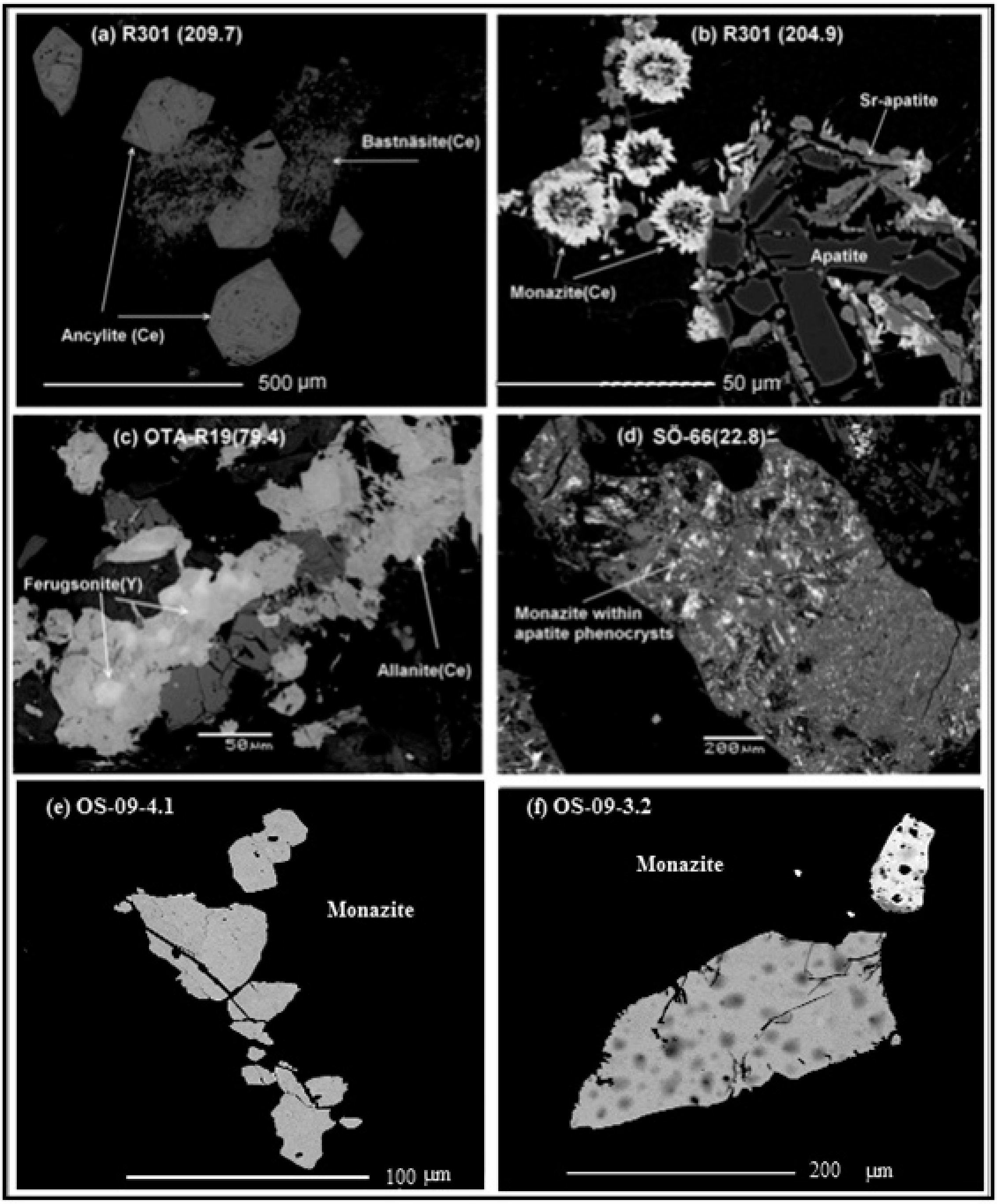

Fig. 2. Examples of backscattered electron images of REE minerals in the studied occurrences:
(a) Hexagonal prismatic ancylite (Ce) pseudomorphing apatite and bastnäsite with ancylite rims or fracture fills, Jammi.
(b) Elongated crystals of apatite with rims and being replaced by Sr-apatite and monazite.
(c) Allanite intergrown with ferugsonite (bright spots), Katajakangas
(d) Clusters of monazite grains within a large apatite crystal, Korsnäs
(e) An aggregate of several monazite grains, Uuniniemi.
(f) Anhedral grains of Th enriched, porous monazite, Uuniniemi.

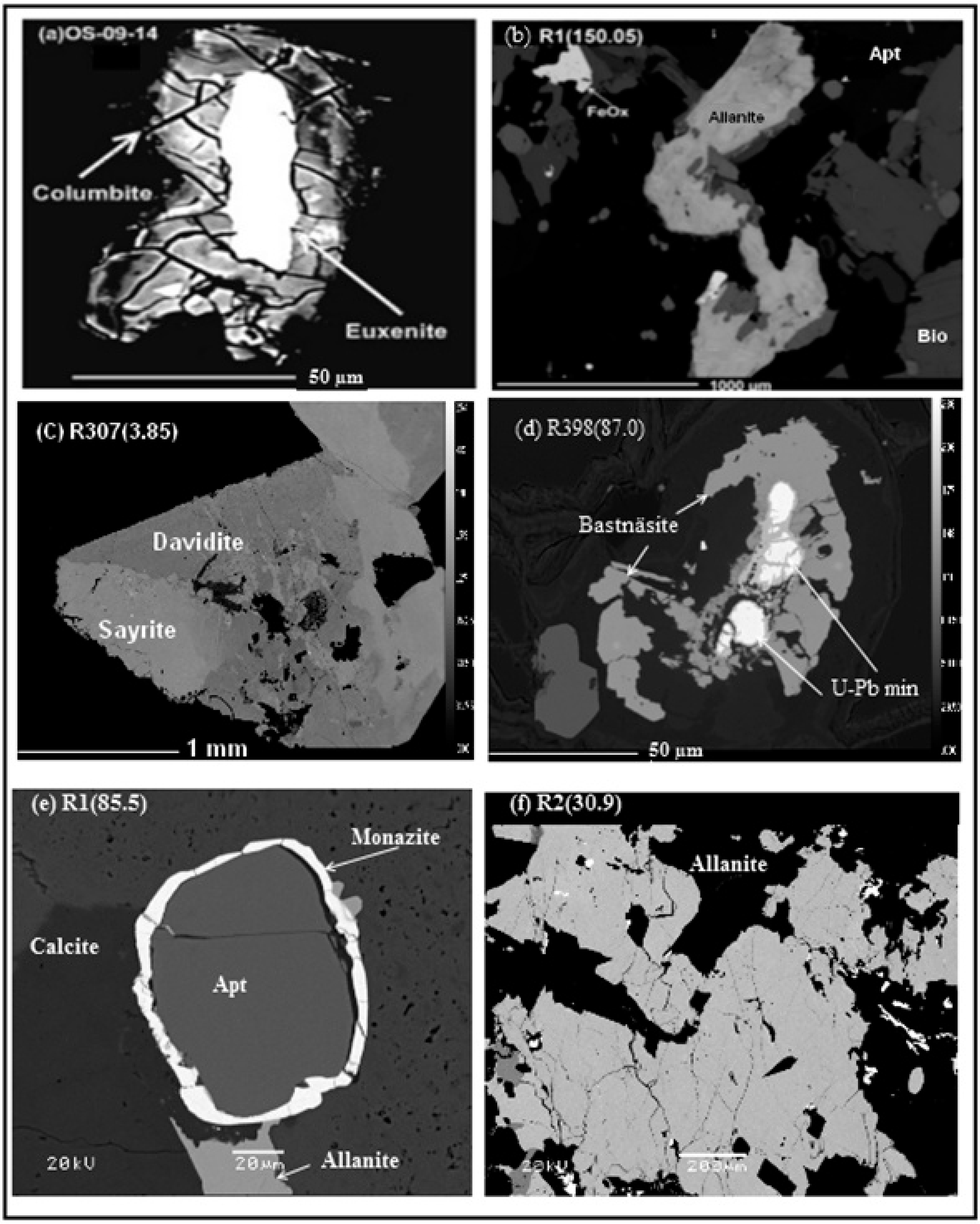

Fig. 3. Examples of backscattered electron images of REE minerals in the studied occurences:
(a) Euxenite crystal (bright) in the core of columbite grain, Mäkärä.
(b) Large subhedral allanite grains intergrown with apatite and biotite, Vanttaus.
(c) Zoned davidite grains zoned in (Pb+U) versus Ti, Palkiskuru.
(d) Bastnäsite surrounded by some U+Pb mineral (bright spots) to show cauliflower form, Honkilehto.
(e) Thinly monazite rimed apatite crystal in calcite, Kortejärvi carbonatite.
(f) Large allanite crystals, Laivajoki carbonatite.

MINERAL DEPOSIT DATABASE

by

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The Geological Survey of Finland is restructuring mineral occurrence data delivery services to meet the demands of new interoperability standards. By the end of 2012, GTK will have combined separate mineral occurrence databases into a single entity. At the same time GTK's mineral deposit viewing and download services will be updated. Due to increasing pressure to create data exchange services ultimately at EU and global scale, the mineral deposit database is based on global geostandards (GeoSciML and EarthResourceML) and related classification recommendations. Viewing and download services based on the database will be designed for various specific purposes (e.g. FODD – INSPIRE – EURARE).

Significant areas requiring the use of geostandards include the dissemination of information in both the EU's INSPIRE directive and The Raw Materials Initiative (RMI). These platforms set new standards for the quality and dissemination of geological data and related metadata. RMI has two particular points for data delivery: 1) The sustainable supply of raw materials located within the EU requires an enhanced knowledge base for European mineral deposits and 2) The Commission recommends better networking between the national geological surveys to facilitate the exchange of information and improve data interoperability and dissemination.

The CGI Council (Data Model Collaboration Group) and its working groups, operating under the IUGS Commission, is responsible for creating unified and internationally accepted standards for disseminating and harmonizing geological data. The Mineral Resource INSPIRE data specification is based on these global standards. Implementation of this content into GTK's databases is also a central objective in the further development and creation of content for the mineral occurrence information system.

GTK's current commodity databases include Au, Zn, Ni, PGE, U, Cu, Industrial minerals, as well as those based on earlier data standards: FODD (Fennoscandian Ore Deposit Database) and ProMine. Migration of the old mineral deposit databases into the new database structure is an ongoing process.

The new database model contains two principal components: the *EarthResource* and the *EarthMaterial.* The *EarthResource* component contains information about mineral occurrence features, along with its associated commodities, exploration activities, mineral resource and reserve estimates, mining activity, production, and waste rocks. The *EarthMaterial* component describes the geology of the mineral deposit. This component contains rock type, alteration, metamorphism, mineralogy, structure, texture and age. Ores, host rocks and wall rocks can be described with great detail in this section.

Five maintenance teams will be established to update database and insert new deposits in it. Teams will be responsible for certain group of deposits which are: 1) Ni, PGE and Fe-Ti-V-Cr, 2) Zn and Cu, 3) Au, 4) U and 5) Industrial and High-Tech minerals. The Mineral Deposit Database will be updated whenever new data (e.g. resource estimates) become available or a new deposit is found.

TECHNICAL SERVICES OF GEOLOGICAL SURVEY OF FINLAND – GROUND GEOPHYSICAL SERVICES

by

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Geophysical surveys are one of the services that the GTK Technical Services provides, along with drilling and sampling services. The total annual turnover of GTK technical services is about 2.5 million euro in a year. The combined ground geophysical component of this is about 900 000 euro. In addition to this GTK annually commits about 800 000 euro to drilling and measurement services provided by external contractors.

This presentation focuses on the choice of various geophysical methods provided by the GTK Technical Services, the costs of the different methods, and the significance of station density in the survey. Project management and resource scheduling is also considered.

GTK offers a wide range of geophysical ground survey methods, including so-called basic surveys covering magnetic, gravity, electrical (IP, mise-a-la-masse), EM (VLF, slingram), seismic and bore hole logging methods. Locating and line staking services including GPS surveys are available. In addition to these GTK offers more specialized geophysical surveys such as TEM, AMT, wide-band EM soundings and ground penetrating radar (GPR) methods. These special surveys are supervised by experts in their respective fields.

There is a continuing need to be up to date and respond to requests for different types of surveys. Sufficient resources are also necessary to guarantee development, renewal, maintenance and training of methods, instrumentation and measuring procedures.

Survey costs can vary considerably, depending on the method and survey grid. For example, a survey area of one square kilometer measured with 20x100 m magnetic grid costs about 1 000 euro while a 10x50 m gravity survey grid costs about 20 000 euro. Deep penetrating specialized surveys such as wide-band EM soundings may be even more expensive.

It is always necessary to define the purpose of the study and the scale of the survey. Low altitude airborne surveys cover whole of Finland and this is a good starting point for geophysical studies and survey planning when combined together with geological information. A survey project workflow can be divided into different stages: the areal classifying phase, the locating and targeting phase and hopefully, the final evaluation phase. Geophysics has a role in each of these phases, starting from sparse grid surveys and continuing to dense grid or profile surveys. The grid density depends on the target of interest. For example in the areal phase, when locating intrusions station spacing may be hundreds of meters while in the targeting phase less than one meter station spacing can be used.

From the point of view of project management in GTK it is important to balance the resource needs to resource availability as effectively as possible. The basic problem in project management is that resource demands pile up during certain seasons, especially when project planning is done on an annual basis. This problem affects all issues relating to resources, measurements, sampling, drilling and analysis and the running sequence of these. Although, these resources are generally sufficient on a yearly basis, scheduling is critical. Therefore, GTK project management should be based more on project life time than on budget year. Projects should also be designed to overlap sequentially so as to avoid the problem of being in the same phase demanding exactly the same resources at the same time.

GOLD IN HUITTINEN, SOUTHERN FINLAND

by

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Svecofennian gold deposits of the Huittinen area, some 160 km NW of Helsinki, lie close to the terrain boundary between the Häme and Pirkanmaa belts and include the Jokisivu gold mine and the Ritakallio, Palokallio and Uunimäki occurrences. (Fig. 1). The Jokisivu area and the Uunimäki prospect form part of the Häme belt and the Palokallio and the Ritakallio gold occurrences are located within in the Pirkanmaa belt (Sipilä et al. 2011). All four gold mineralizations are hosted by shear or fault zones within mafic intrusions. Ages of the Svecofennian gabbros and quartz-dioritic rocks are typically 1.88 Ga (Suominen 1988, Kilpeläinen 1998).

The Ritakallio gold occurrence was found by the Geological Survey of Finland when drilling geochemical and geophysical anomalies in 2002 (Vuori et al. 2005). The first indications of gold were slightly elevated (21 ppb) gold concentrations in till in a regional geochemical survey, and the discovery of numerous mineralized boulders and gold grains in till during a follow-up survey (Huhta 2004). A quartz dioritic to gabbroic intrusion, similar to that at Jokisivu, contains NE- to NNE-dipping gold-bearing quartz veins in shear zones. Gold-bearing veins are associated with alteration of the wall rock. Alteration is characterised by the presence of sulphides, sericite, K-felspar, and quartz. Gold occurs in native form as free grains between silicate gangue minerals and as inclusions in sulphides, with the grain size ranging from <0.01 up to 1 mm (Lahtinen 2005). Gold also forms composite grains with Bi-, Sb- and Te-rich minerals. Dragon Mining has been exploring the area and has obtained promising results, including a narrow high-grade intercept of 1.10 m at 49.80 ppm Au (Dragon Mining 2011).

The Geological Survey of Finland investigated the Palokallio occurrence during 2006–2009. The gold mineralisation is hosted by centimetre-scale shear zones within a gabbro. The gabbro is intruded by mafic dykes, granitic pegmatite dykes and quartz veins and is surrounded by mica gneisses and graphite-bearing sulphide schists. The best gold grade intersected during drilling is 41.8 ppm along a 0.9 m interval. Gold grades in drill core samples are usually below 1 ppm/1 m. Arsenopyrite, löllingite, pyrrhotite and scheelite are the most abundant ore minerals (Voipio 2008, Grönholm & Voipio 2012).

The Uunimäki gold prospect was discovered during 2009 by drilling a gold and scheelite anomaly based on heavy mineral sampling of till. The till sample was taken close to a shear zone localized during mapping gold Au-critical mafic intrusions in the Huittinen area. Geophysical features and lithology at Uunimäki are similar to those at Ritakallio. The gabbro includes disrupted and brecciated zones, with relatively weakly deformed gabbro fragments within a matrix of fine-grained epidote, chlorite, quartz and carbonate, thin quartz vein networks, and locally sulphides. The gabbro is heterogeneous, and outside the fault zones only weakly deformed. Au-enriched zones in drill core typically occur over 2 to 5 m intervals with 2 – 3 ppm Au, the highest grade detected being 15 ppm Au along a one metre intercept.

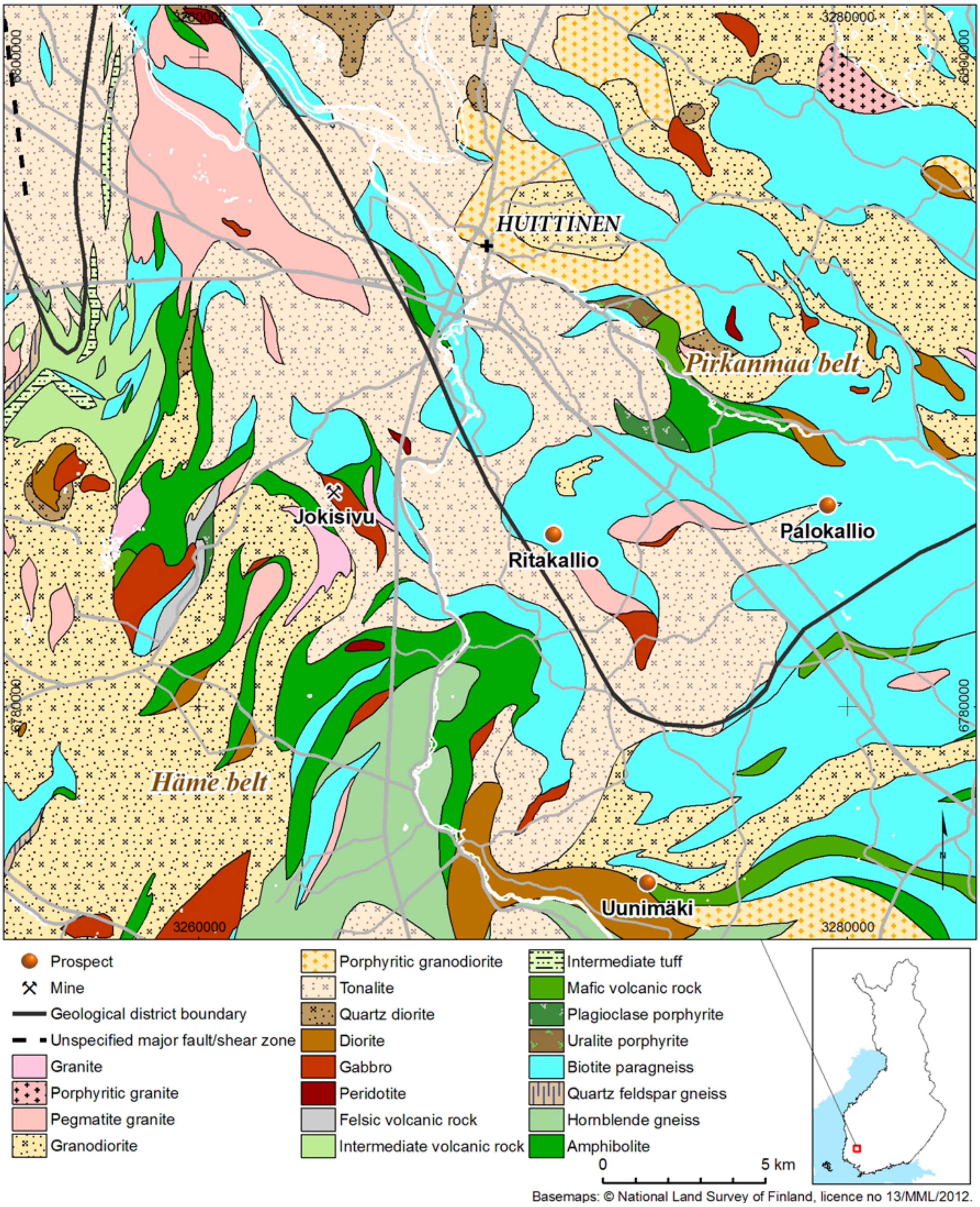

Fig. 1. Location of the Jokisivu, Ritakallio, Palokallio and Uunimäki gold prospects. Geology after Geological map by the Geological Survey of Finland (Bedrock of Finland–DigiKP), and recent exploration by GTK (Sipilä et al. 2011).

Typical ore minerals include locally abundant pyrrhotite, and minor chalcopyrite, arsenopyrite and ilmenite. The Au-critical area also correlates with a distinct IP anomaly.

However, the gabbros and quartz diorites hosting the gold mineralisation in the Huittinen area are not readily distinguishable from their surroundings in terms of their magnetic, electromagnetic or radiometric signatures. Typically the only magnetic mineral is monoclinic pyrrhotite, and the susceptibilities of these rocks usually remain low (Huuskonen 2009, Mertanen & Karell 2012). In the gravimetric maps, the NW–SE-trending gold potential zones appear to be related to gravity minima (Vuori et al. 2007). Gold-critical major shear zones are also recognized in aeromagnetic maps as diffuse non-magnetic and locally gently curving lineaments. These four gold occurrences demonstrate that shear zones in mafic intrusions are of high gold potential in the Huittinen area, and likely also elsewhere in the Svecofennian area, as already demonstrated by the extent of known mineralisation at Kaapelinkulma and Laivakangas.

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NEW PGE-Cu-Ni OBSERVATIONS FROM THE EARLY PALAEOPROTEROZOIC JUNTTILANNIEMI LAYERED INTRUSION, PALTAMO, EASTERN FINLAND

by

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The recently identified Junttilanniemi layered intrusion is located in the Varisniemi area, c. 25 km southwest of the Paltamo town, in Oulu Province (Fig. 1). The main purpose of the present study was to assess the PGE-Cu-Ni ore potential of the 2443±7 Ma Junttilanniemi intrusion (Asko Kontinen 2006, personal communication) and find out whether it was the source of the PGE-rich (Ni 0.14%, Cu 0.38%, S 0.7%, Pd 6.83 ppm, Pt 1.56 ppm and Au 0.18 ppm) gabbronorite boulder (glacial float) found by an amateur prospector from the Näätävaara area, to the north of the town of Nurmes (Halkoaho & Niskanen 2011).

During the winter of 2010, when Lake Oulujärvi was suitably frozen, a profile of five (5) diamond drill holes, totalling to 563.90 m, were drilled in the southernmost (submerged) part of the Junttilanniemi layered intrusion, in the Karhusalmi area. Drilling results showed that the lowermost part of the intrusion comprises three ultramafic units. The interface between the chromium-rich and chromium-poorer rock units in the lower part of the intrusion was located, as were five separate layers enriched in platinum-group elements (Figs. 2 and 3). None of the drilled profiles showed PGE concentrations as high as those in the Näätävaara boulder (PGE+Au = 8.57 ppm), the highest PGE+Au value obtained being about 0.8 ppm, in the uppermost PGE enriched layer (cf. Fig. 3). The highest analyzed abundances of nickel, copper and sulfur were 0.18%, 0.45% and 0.97%, respectively, being determined by ICP-OES from solutions after aqua regia digestion of 0.15 g samples (Labtium Oy, analytical method 511P). However, noting that only one cross-section through the PGE enriched layers has so far been drilled, we cannot yet conclusively discount the possibility that the Näätävaara boulder may originate from the Junttilanniemi intrusion.

Several chromite-rich boulders found previously in the Varislahti area, several kilometres NNW of the Junttilanniemi intrusion indicate that there may be an additional Palaeoproterozoic layered intrusion(s) in this unexposed area, which could be an alternative source for the Näätävaara boulder.

To further study the PGE distribution in the Junttilanniemi intrusion, a deep diamond drill hole from the shoreline of Lake Oulujärvi is recommended. This is feasible as the distances from the Ojaniemi and Kuikkaniemi headlands to the lower contact of the intrusion are only about 700 m and 450 m, respectively.

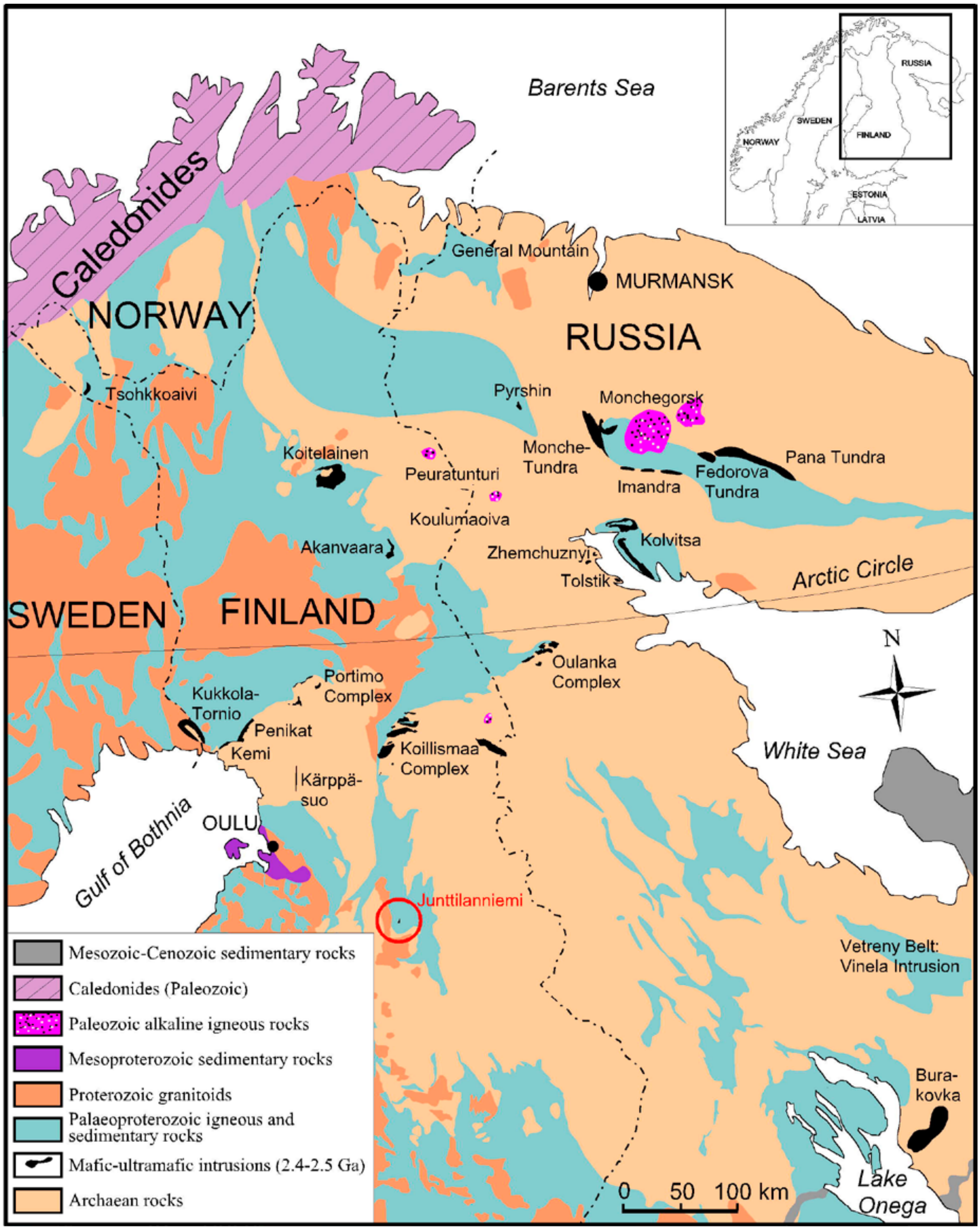

Fig. 1. Generalized geological map of the northeastern part of the Fennoscandian Shield and locations of early Palaeoproterozoic layered intrusions (modified from Alapieti et al. 1990 and Karinen 2010).

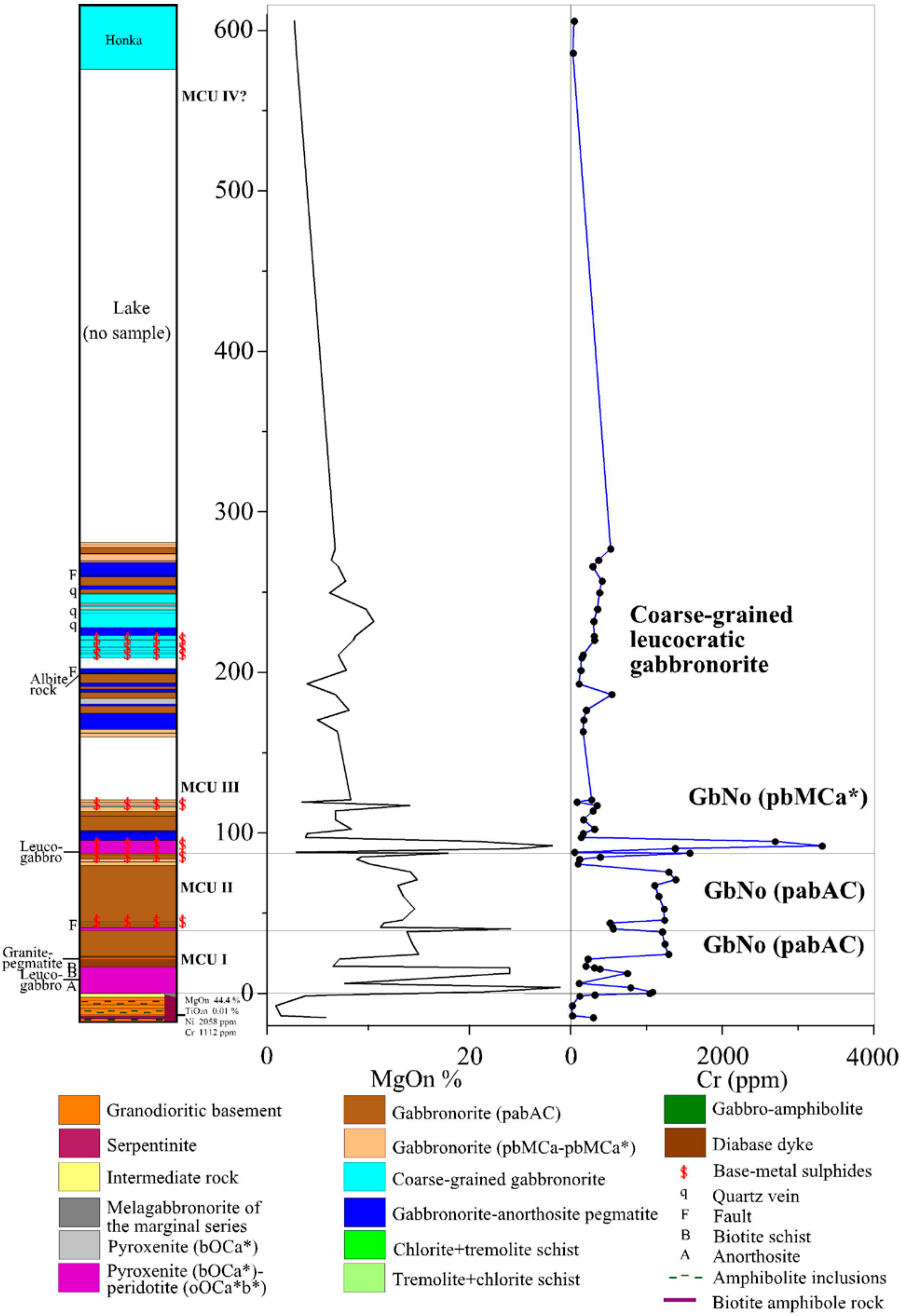

Fig. 2. Lithological column for the SE part of the Junttilanniemi intrusion with graphs showing variations in volatile-free recalculated MgO and chromium (determinations by XRF, method 175X of Labtium Oy).

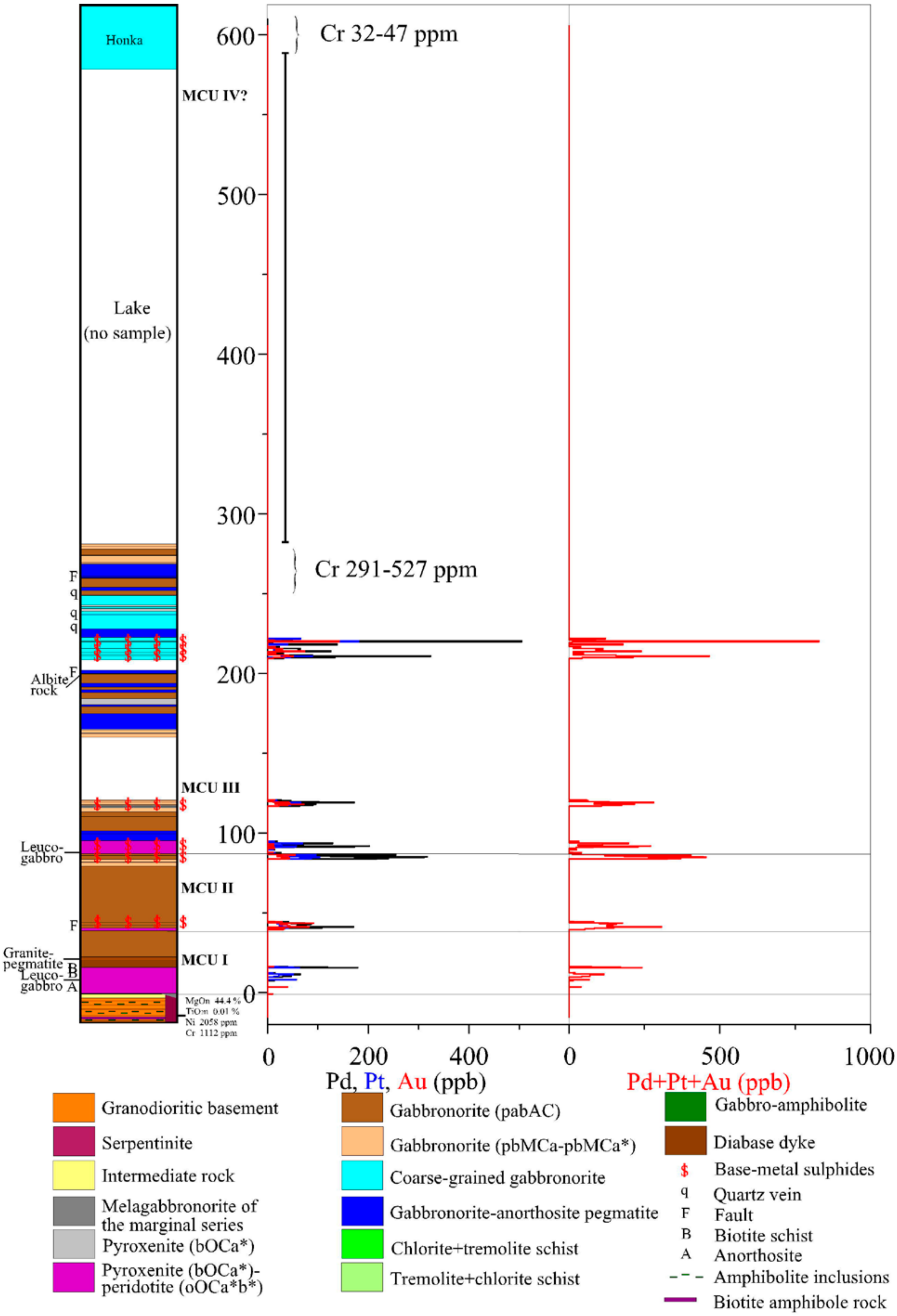

Fig. 3. Variations in palladium, platinum and gold (determinations by ICP-AES, method 704P of Labtium Oy).

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A NEW TYPE OF Sc-Zr OCCURRENCE LOCATED IN THE KIVINIEMI AREA, RAUTALAMPI, CENTRAL FINLAND

by

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A new type of Sc-Zr occurrence has been recently located at Kiviniemi, some. 22 km north of the town of Rautalampi, in central Finland (Fig. 1). The initial reason for investigating the Kiviniemi area was to assess the Ni-Cu potential of a gabbroic intrusion. However, instead of the anticipate Ni-Cu, the study resulted in the discovery of an interesting Sc-Zr occurrence.

During the years 2008–2010, nine (9) diamond drill holes were drilled in the Kiviniemi area, totalling 1251.80 m. The main rock type in the Kiviniemi prospect area is areddish granite with phenocrysts of potassium feldspar. The granite encloses a body of dark coloured, fine- to medium-grained gabbroic rock. The northern-most corner of this gabbroic body consists mainly of coarse-grained to pegmatitic garnet-bearing fayalite ferrogabbro/diorite. The area of the pegmatitic occurrence is about 2.5 hectares, and there is also a small (about 100 long and 20 m wide) satellite occurrence of similar rock some 50 m to the NE of the main body. In addition to gabbro these two bodies also include leucocratic ferrogabbro/diorite and diorite. The U-Pb zircon age of the pegmatitic garnet-bearing fayalite ferrogabbro/diorite is 1857±2 Ma (A2024, Huhma 2010, written communication).

The main silicate minerals in the pegmatitic garnet-bearing fayalite ferrogabbro/diorite are plagioclase (An30.7–44.7), potassium feldspar, ferrohedenbergite, ferrohastingsite, fayalite (Fo2.8) and almandine garnet. Zircon, apatite, ilmenite, quartz and pyrite occur as accessory minerals. All of the above mentioned rock types, apart from granite, are characterized by high zirconium (mostly > 1000 ppm) contents. It is noteworthy that only zircon grains in the pegmatitic garnet-bearing fayalite ferrogabbro/diorite fluoresce golden under ultraviolet light (Fig. 2). The main carriers of scandium are ferrohedenbergite and ferrohastingsite, having average scandium contents of 735 ppm (number of analyses = 13) and 837 ppm (n=5), respectively. In addition, zircon contains on average 187 ppm scandium, as well as 0.92% hafnium (n=12). Apatite contains on average 540 ppm yttrium (n=3).

The highest analyzed contents of scandium (drill core sample length 1.1 m), zirconium (sample length 0.85 m) and yttrium (sample length 1.3 m) are 293 ppm, 6760 ppm and 255 ppm, respectively, concentrations having been determined by ICP-OES from solution after sodium peroxide fusion of 0.2 g samples

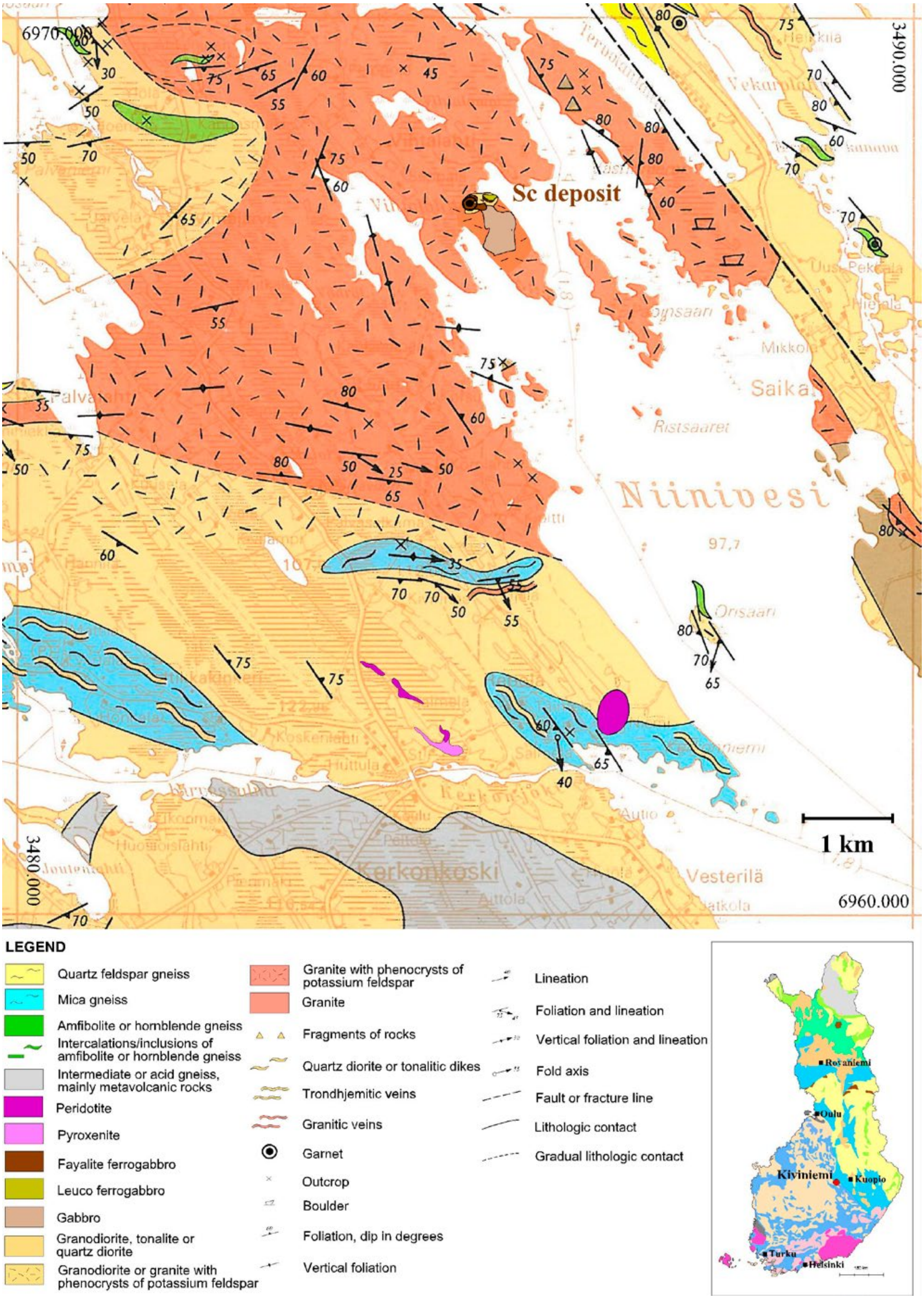

Fig. 1. Geological map of the Kerkonkoski area, Rautalampi, showing the location of the Kiviniemi Sc-Zr occurrence. Modified after Pääjärvi (1991, 2000). Delineation of ultramafic rocks in the area to the north from the Kerkonjoki river is after Makkonen and Forss (2000).

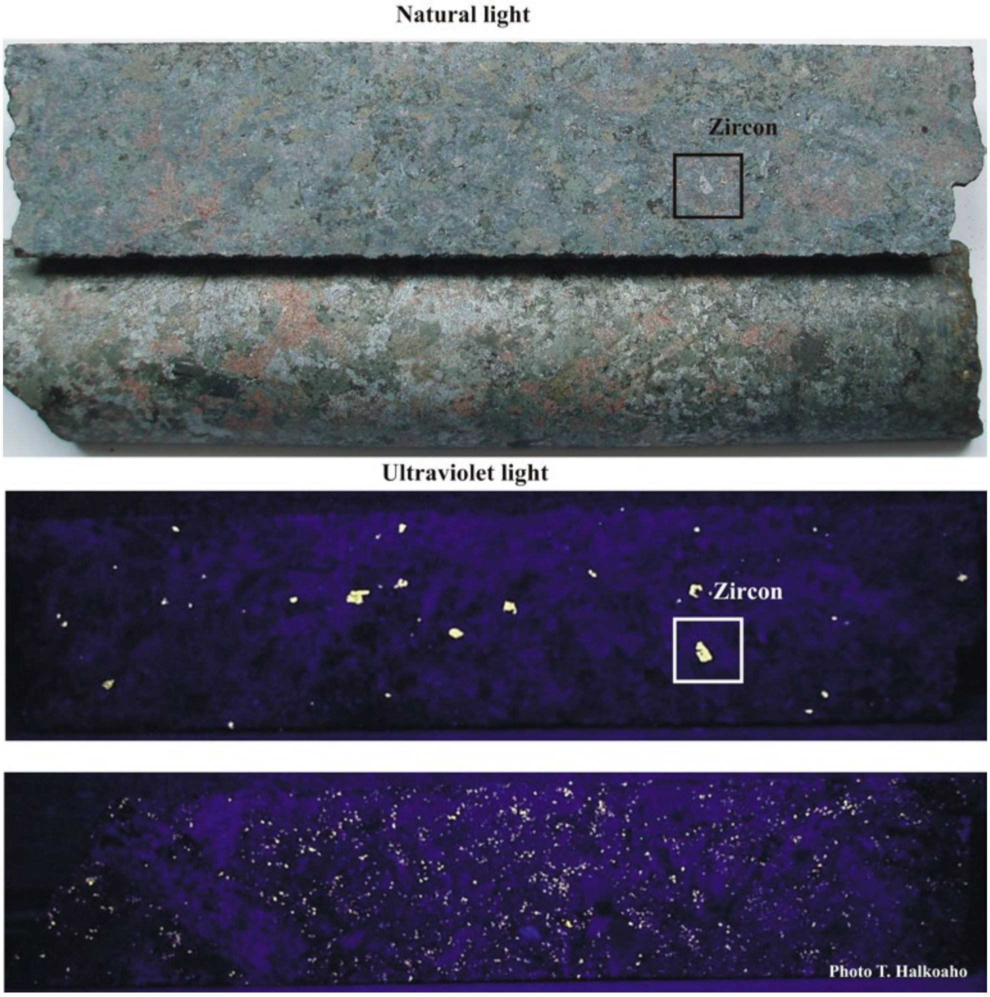

Fig. 2. Photographs of drill core samples from the garnet-bearing fayalite ferrogabbro/diorite typical of the Kiviniemi Sc-Zr occurrence. The upper photographs shows the sample under natural light and lower ones ultraviolet light. In the upper images, the reddish mineral is almandine garnet, the grayish minerals are plagioclase and potassium feldspar, the dark green mineral is ferrohastingsite, the green mineral is ferrohedenbergite and the light green mineral is fayalite. In the lower images the yellow spots pick up zircon grains. The width of the drill core is 4 cm.

in a Ni crucible (Labtium Oy, analytical method 724P).

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AMMONIUM ACETATE LEACHING OF TILL SAMPLES AS AN ORE PROSPECTING TOOL IN SE-FINLAND

by

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Altogether 131 till samples were collected at three separate targets close to the contact of rapakivi granite and biotite paragneiss in south-eastern Finland, to locate anomalies for follow-up prospecting. An ammonium acetate leach was applied for analyzing ions that are weakly bound to the surfaces of grains. The samples were collected at a depth of 20-40 cm from pits made by spade and thereafter extracted in 1 M ammonium acetate at 4.5 pH. An extensive range of elements was analyzed by ICP-OES and ICP-MS at the Labtium plc laboratory in Espoo.

Although the overall abundances were very low, the differences between the lowest and the highest concentrations of several elements were over orders of magnitude, indicating the functionality of the method.

At the Mustapää target in Savitaipale, samples were collected along two traverses on the northwestern side of the discovery site of a nickel-rich glacial boulder. The REEs abundances were highly anomalous, and thorium and uranium contents were high in the rapakivi part of the traverses. A distinct Pb-Zn-Ag anomaly was recorded on both sides of the contact zone between the rapakivi granite and mica gneiss, although interpretation of airborne geophysical suggested that follow-up survey is not warranted. Nickel contents were low along both of the traverses.

The nickel contents of the Ahokkala traverse in Taipalsaari were mostly low, but very anomalous Ni and Ni x Ni/Ce ratios were found in the vicinity of a small known nickel mineralization.

The nickel mineralization at the Kuurmanpohja target in Lappeenranta was also indicated by extremely high Ni x Ni/Ce values, being almost 100 times greater than the mean value.

The weak leaching method is clearly well-suited to ore exploration. One, probably crucial, precondition for the positive outcome was the prevailing warm and dry weather prior to sampling. This made capillary action in the soil effective, allowing the ions to rise to the surface, while rain waters would have transported the ions deeper into the soil horizon.

LATE ARCHEAN ALKALINE SYENITES IN THE LENTUA COMPLEX

by

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INTRODUCTION

The Lentua complex (formerly known as the Kianta Complex) forms an extensive part of the western Karelian subprovince in Finland (Fig. 1, Hölttä et al. 2012). The granitoid rocks of the Lentua Complex have so far been divided into four major suites: (tonalite-trondjhemite-granodiorite) TTG gneisses (2.95–2.75 Ga), sanukitoids (~2.72 Ga), quartz diorites (2.72–2.69 Ga) and anatectic leucogranitoids (a.k.a. granite-granodiorite-monzogranite series [GGM]) associated with extensive migmatization (2.70–2.68 Ga) (Käpyaho et al. 2006, 2007, Heilimo et al. 2010, 2011, Mikkola et al. 2011a, 2012). The greenstone belts in the area are dominated by mafic volcanic rocks, mainly 2.84–2.79 Ga in age, occurring as relatively narrow N–S narrow trending zones (e.g., Luukkonen, 1992, Papunen et al. 2009). Large parts of the southern Lentua complex consist of Nurmes-type paragneisses, derived from immature greywackes, with Neoarchean (2.75–2.70 Ga) protolith ages (Kontinen et al. 2007). Here we give a brief overview of another group of granitoids, namely syenites, which have so far received less attention than other rock types. Our overview is based on both previous results (Huhma 1975, Paavola 2006, Mikkola et al. 2011b) and new data (field observations, compositional data, age determination) obtained during recent and ongoing bedrock mapping. Most of the syenites are likely to be temporally coeval with the quartz diorites and leucogranitoids.

FIELD DESCRIPTIONS

So far, six relatively small (ca. 1 x 2 km^2) and one larger felsic syenite intrusions have been identified within the Lentua complex. The modal compositions of the intrusions vary from syenite, quartz syenite to monzonite and quartz monzonite. The rocks are commonly non-foliated or weakly foliated and contain an-

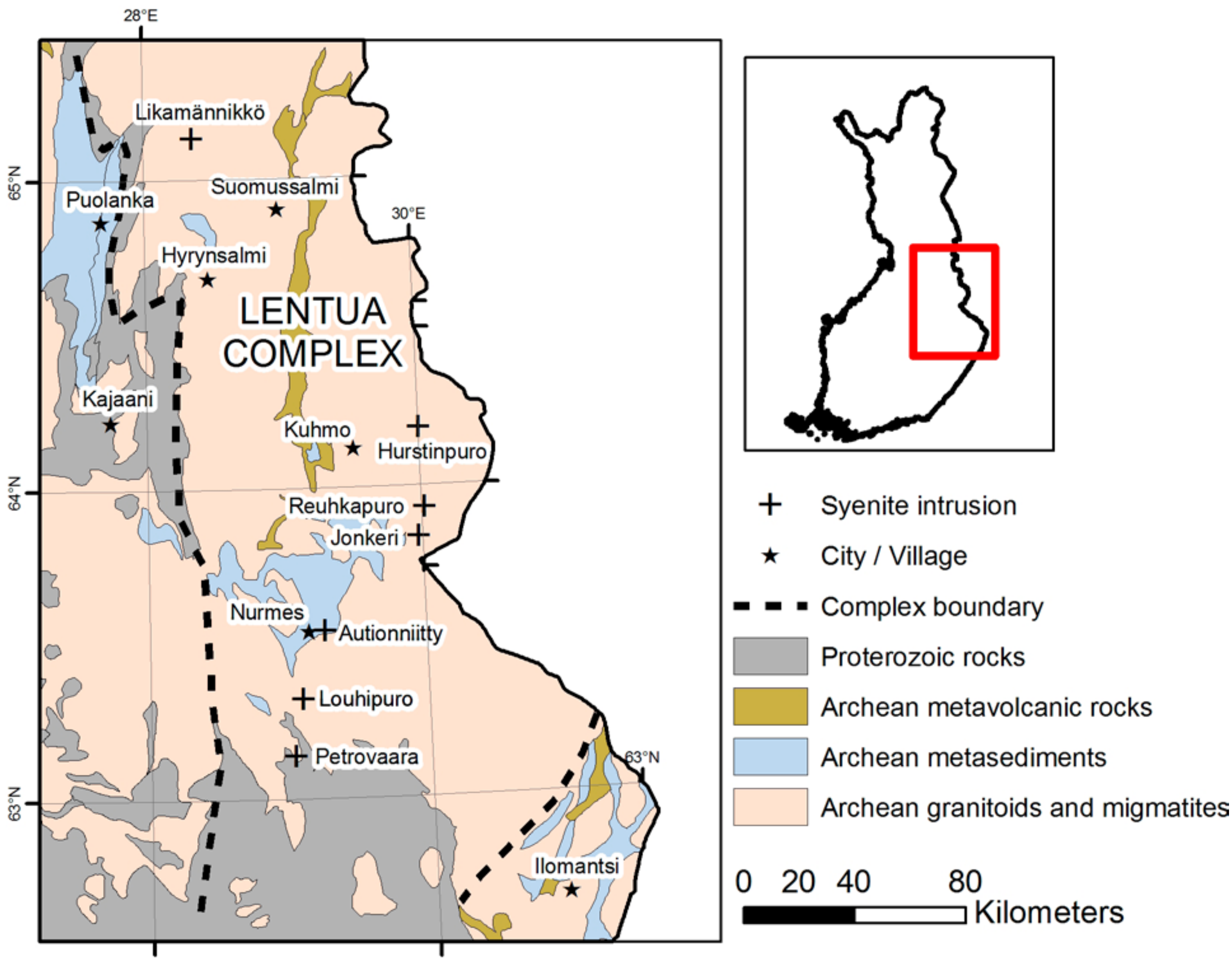

Fig. 1. Geological map showing the syenite intrusions in the Lentua complex in Finland.

gular country rock xenoliths. Sharp intrusive contacts are a distinctive feature in which the syenites differ from Archean leucogranites, and K-metasomatized TTGs, which typically display gradual contacts with country rocks. Petrographically, the syenites are granular, and vary from small K-feldspar porphyritic to even-grained. The mineralogy of the syenitic rocks are K-feldspar, plagioclase, quartz, hornblende and in some intrusions also clinopyroxene and biotite.

ELEMENTAL COMPOSITION

The syenites are generally metaluminous and contain high total alkalis (Na_2O+K_2O=7.0–12.8 wt.%, with K_2O/Na_2O ~ 0.5–1.45). Major elements, except Al_2O_3, K_2O, and Na_2O, decrease with increasing silica (Fig. 2), while SiO_2 abundances are generally between 60 and 70 wt.%, and K_2O between 3.0 and 6.0 wt.%, so that compositions typically classify as shoshonitic. Chondrite-normalized REE patterns are enriched in LREE (La_n=25–1000), having $(La/Yb)_n$ values between 10 and 80, with Eu anomalies varying from slightly positive to negative. Compositional differences between individual syenite intrusions are considerable, for example with respect to Na_2O, Ba and Sr. Compositionally the syenite group displays certain features, such as high total alkalis and relatively high Ga/Al values typical for A-type granites (e.g., Whalen et al. 1987). The syenite group differs compositionally from the other Archean granitoid groups, including TTGs, sanukitoids and quartz diorites as well as leucogranitoids. Compared to "classical" low-HREE TTGs (a.k.a. high pressure TTGs) syenites have lower Al_2O_3 concentrations at a given SiO_2 content. The Na_2O, and K_2O as well as Ba, and Sr concentrations are higher in syenites than in sanukitoids. The major geochemical difference between syenites and leucogranitoids is the lower SiO_2 content of the syenites.

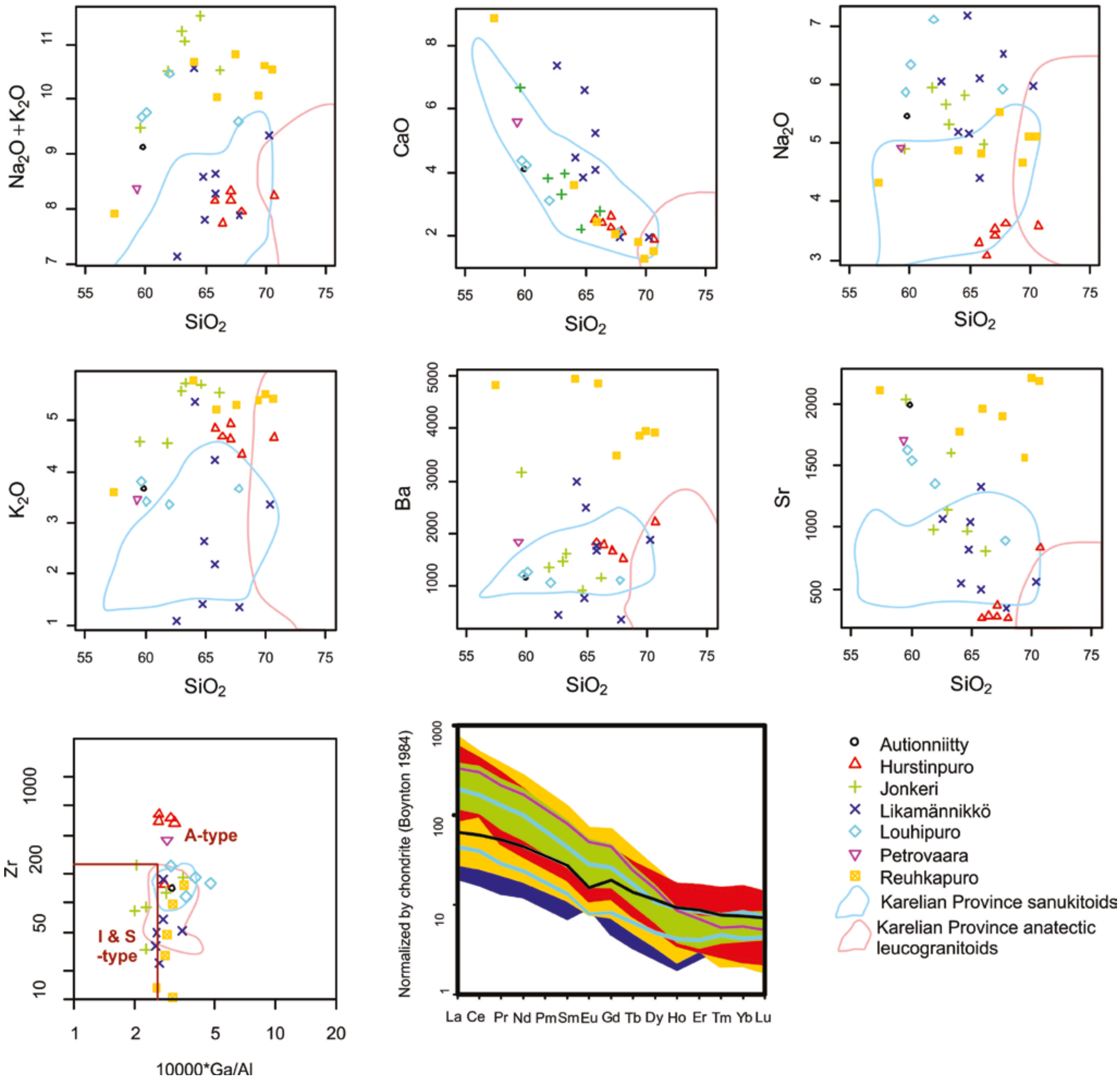

Fig. 2. Some geochemical features of Lentua complex syenites compared to sanukitoids (e.g. Heilimo et al. 2010) and leucogranitoids (Mikkola et al. 2012) of the Karelian Province. Symbol colors show the intrusions in the chondrite normalized REE patterns.

AVAILABLE ISOTOPE DATA

We are currently collecting representative samples to constrain the emplacement ages of the syenite group. So far, two of the syenite intrusions (Jonkeri and Likamännikkö) have been dated using the zircon U–Pb method (Fig. 1).The Jonkeri monzonite is, despite being larger than most of the intrusions, very representative of the syenite group and yielded a concordant U–Pb age of 2704±9 Ma with the LAMS method. The whole-rock Sm–Nd data from the Jonkeri sample provides an initial ε_{Nd} -1.7 giving T_{DM} model age of about 2.96 Ga (unpublished). Likamännikkö is an atypical syenite intrusion, being associated with abundant ultramafic fragments and some carbonatite patches (Mikkola et al. 2011b) and is also located 200 km north of the area hosting the majority of the syenite intrusions (Fig. 1). This intrusion yielded a concordant U–Pb zircon age of 2741±2 Ma using conventional TIMS. Initial ε_{Nd} values from Likamännikkö intrusion indicate juvenile source. The carbonatite patches from Likamännikkö show mantle like stable isotope values $\delta^{18}O_{VSMOW}$ between 5.2 and 5.5 ‰ and $\delta^{13}C_{VPDB}$ between -3.8 and -5.5‰ (Mikkola et al. 2011b).

COMPARISON TO OTHER ARCHEAN DOMAINS

Some other late Archean domains, e.g. Yilgarn Craton (Smithies & Champion 1999), Superior Province (Feng & Kerrich 1992), and Greenland (Blichert-Toft et al. 1995), that have been studied in more detail contain similar group of syenitic intrusions, both compositionally and temporally (with respect to respective regional geological evolution). The proposed petrogenetic interpretations for Archean syenites vary from partial melting of lower crust to partial melting of enriched mantle via strong fractional processes. We are currently attempting to chemically and isotopically characterize the syenites of the Lentua Complex to better understand the crustal formation processes during the Neoarchean in the Karelian Province.

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MODELLING AIRBORNE TRANSIENT ELECTROMAGNETIC MEASUREMENTS

by

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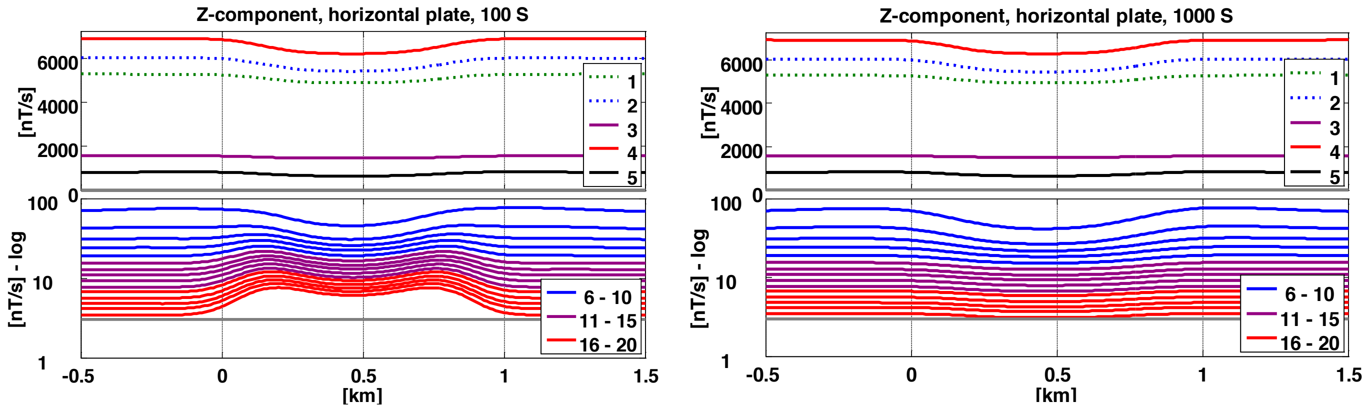
We have compared modern airborne electromagnetic (AEM) time domain (TEM) systems by using forward modelling to calculate theoretical responses for VTEM, SkyTEM and MEGATEM equipment, using software developed by CSIRO in the AMIRA P223 project. VTEM (Geotech 2008) and SkyTEM are essentially similar helicopter-borne TEM-systems. MEGATEM (and GEOTEM) (Ontario Geological Survey 2002) is a powerful fixed-wing TEM system. These theoretical simulations are based on reported configurations and given noise levels, which are not necessarily up-to-date. However, these different theoretical AEM studies can be used to characterize different aspects of real airborne TEM measurements.

The time domain method is based on the electromagnetic induction. A primary magnetic field is transmitted as a train of alternating pulses with an off-time following each pulse. The magnetic pulses cause eddy currents to flow within bedrock conductors, generating a decaying magnetic secondary field. The rate-of-change of the magnetic field is measured on time channels by a receiver coil. The measuring time of a TEM system is usually represented as the base frequency, where the width of the pulse and the following off-time period form a half cycle of the frequency.

We have studied the effect of the base frequency, the required range of the off-time channels for measuring the time derivative of the magnetic field dB/dt, the advantages of B-field acquisition (by integrating the on- and off-time dB/dt responses), and the usefulness of the on-time dB/dt (measured during the pulse).

VTEM has a central loop configuration, where the two receivers are in the center of the horizontal transmitter loop (area 531 m^2 or 962 m^2). The receiver coils measure the vertical (z) and the horizontal in-line (x) component of the time derivative of the magnetic field dB/dt. The integrated B-field components are produced. The nominal terrain clearance of the transmitter is about 34 m. Base frequency is selectable over the range 25–200 Hz. In our calculations we have used a peak current of 219.4 A for the transmitter, which with four turns of cable yields a moment of 466 000 Am^2.

In the SkyTEM system the receiver coils for the z- and x-components of dB/dt are placed above and slightly behind the horizontal transmitter loop (area 494 m^2). It is possible to use two base frequencies on the same measurement flight e.g. 25 Hz and 222 Hz, enabling the measurement of a wider range of off-time dB/dt



a) b)

Fig. 1. Megatem anomaly of a conductive plate. A 800 by 800 m horizontal plate is located at a depth of 200 m in bedrock of 2000 Ωm with the overburden 10m thick having conductivity of 100 Ωm. Channels 1 and 2 (dotted lines) have negative values but are given here as absolute values.

responses. The terrain clearance is about 30 m. In our calculations we have used a peak current of 9 A with one turn of cable for the base frequency of 222 Hz and 91 A with four turns of cable for the base frequency of 25 Hz. The corresponding moments are 4 446 Am^2 and 179 816 Am^2 respectively.

The MEGATEM system is mounted on an aircraft such that the transmitter loop (area 406 $m^{2)}$) is wound around the nose, the wing tips and the tail of the aircraft. The three component dB/dt-receiver is towed by the aircraft, 50 m below and 131 m behind the center of the transmitter loop. The responses are measured both on-time and off-time. The nominal terrain clearance for the transmitter loop is 120 m and for the receiver 70 m. Base frequencies are 150, 90, 30, 125, 75 and 25 Hz. In our calculations we have used a peak current of 810 A with five turns of cable yielding a moment of 1 640 000 Am^2.

In the case of highly conductive bodies the TEM-anomaly may vanish from the off-time results but is still detectable in the on-time response. This is illustrated in the MEGATEM anomaly in Figure 1, where a 800 by 800 m horizontal plate is located at a depth of 200 m below the ground surface, where the bedrock has a conductivity of 2000 Ωm and overburden has a thickness of 10 m and conductivity of 100 Ωm. If the conductivity thickness product is 100 S, the off-time anomaly is clearly visible in later channels (16-20) in the lower part of Figure 1a. If the conductivity thickness product is raised to 1000 S the same anomaly has almost vanished, as in figure 1b. However, the on-time anomalies are almost identical in the upper parts of the figures.

The aim is to determine how these theoretical AEM systems are able to detect and resolve deep electrical conducting targets of varying shape and size. We are particularly interested in the depth of investigation, when the target is electrically very conductive.

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SM-ND ISOTOPES AND AGE OF PALAEOPROTEROZOIC MAFIC ROCKS IN FINLAND – EVIDENCE FOR RIFTING OF ARCHAEAN LITHOSPHERE AND MULTIPLE MANTLE SOURCES

by

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Isotopic studies on mafic dykes, intrusions and volcanic rocks in Finland have revealed rifting of the Archaean lithosphere at several distinct stages including ca. 2.44 Ga, 2.3 Ga, 2.22 Ga, 2.15– 2.11 Ga, 2.05 Ga, 2.0 Ga, 1.95 Ga and 1.8 Ga (Fig. 1). Much of the relevant age data have already been published in the special volume containing U-Pb data on more than 180 samples from Finnish Lapland (Vaasjoki 2001). Many of these results date gabbroic rocks from larger intrusions and dykes, and can also be used to reliably constrain the ages of mafic volcanic events, which have produced the major mafic formations especially in Central Lapland. Mafic rock associations in the Karelian domain provide time-integrated probes either from the lithospheric mantle below the Archean craton, asthenospheric depleted mantle or mantle plumes from deeper sources. Some mafic rocks may be regarded representing ancient Large Igneous Provinces.

Samarium-neodymium mineral and whole-rock analyses have been made at GTK since the early 1980's. The database currently includes more than 500 analyses on ~ 70 Palaeoproterozoic mafic rock units in the Karelian domain. The emphasis has been on sampling the most pristine available rocks and generally the Sm-Nd mineral ages on such relatively well-preserved samples are consistent with their respective U-Pb zircon ages. As many of the initial ε_{Nd} values are based on the Sm-Nd mineral isochrons, they should give reliable estimates for the initial isotopic composition of the rocks in question. These data together with U-Pb ages and geochemical and other geological information provide tools for constraining the age and origin of the magmas of the major mafic episodes and thereby the evolution of lithosphere and mantle components.

The initial ε_{Nd} values range from very positive to strongly negative (Fig. 2). High initial values suggest derivation from depleted mantle sources, whereas low values point to a large contribution from old enriched continental lithosphere.

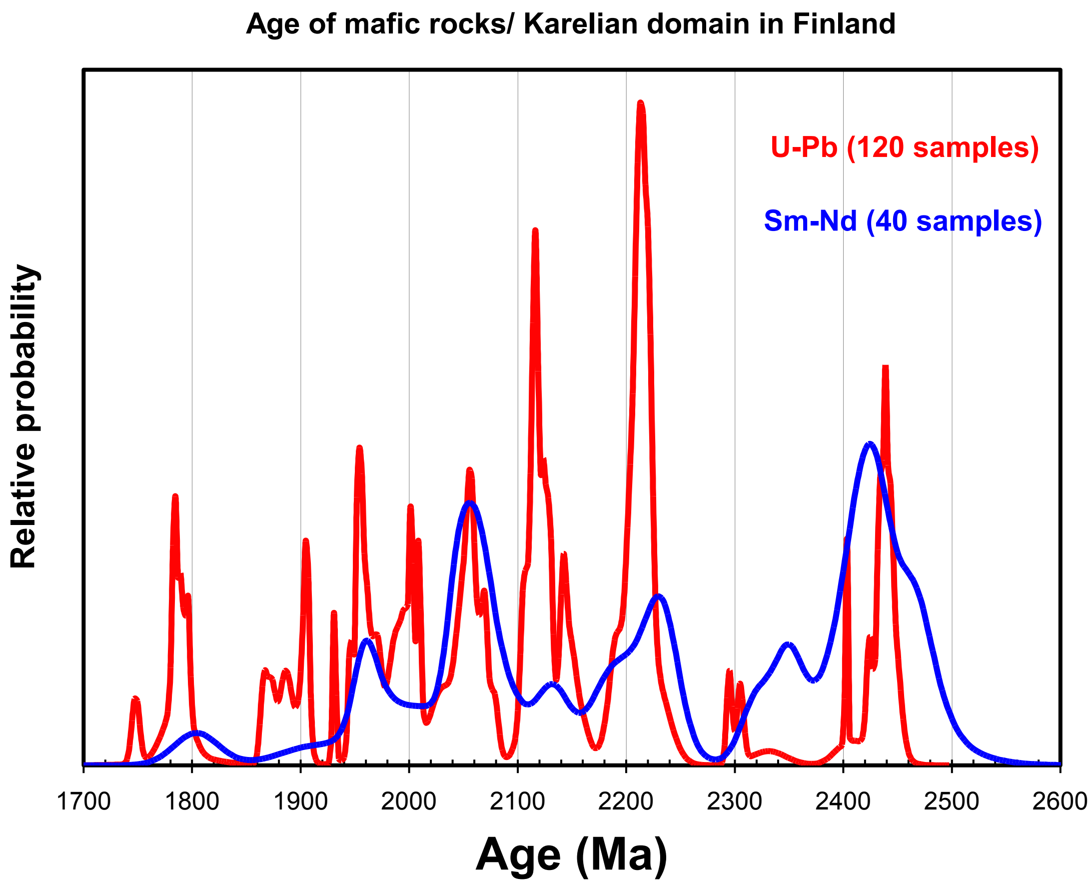
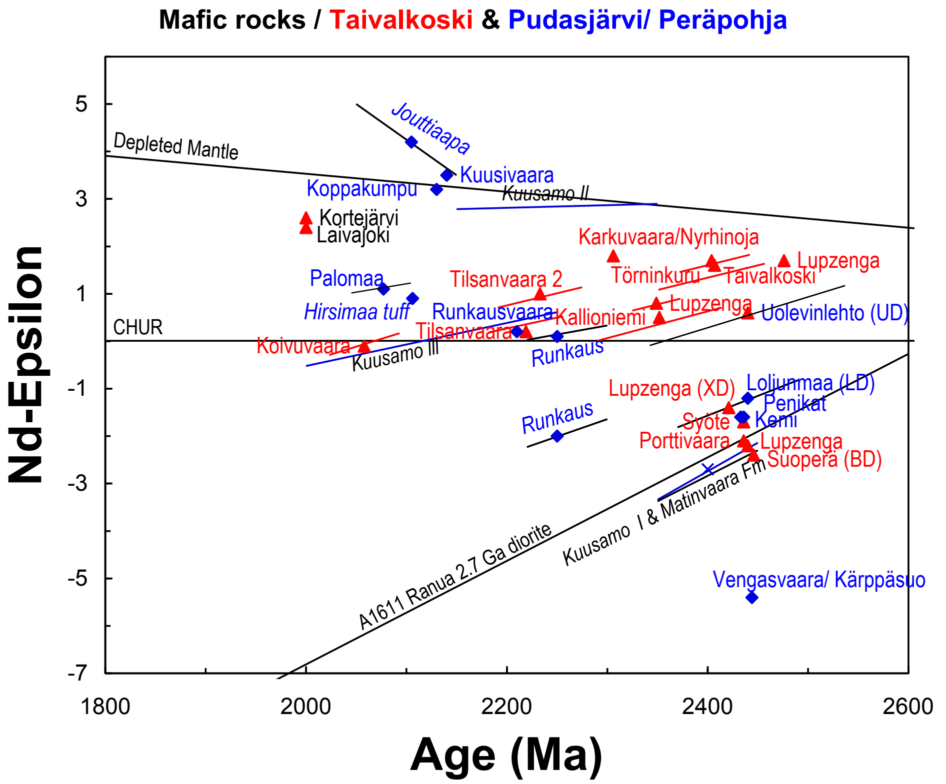


Fig. 1. Probability density plot of U-Pb (red, 120 samples) and Sm-Nd (blue, 40 samples) ages on Palaeoproterozoic mafic rocks from the Karelian domain in Finland. The Sm-Nd ages are mostly based on analyses on whole rock, pyroxene and plagioclase and have an average error of 40 Ma (Huhma et al. 2011).

Crustal contamination of ultramafic magma at depth may explain many features observed in such rocks as e.g. the 2.44 Ga layered mafic-ultramafic intrusions with ε_{Nd} of −2, but the isotopic results also show that various mantle sources with distinct isotopic compositions must have existed during the Palaeoproterozoic. Evidence of this is provided by high-REE mantle-derived rocks showing a range of initial ε_{Nd} values from nearly chondritic (e.g., the 2.61 Ga Siilinjärvi carbonatite, 1.95 Ga Jormua OIB, 1.78 Ga lamprophyres) to highly positive (e.g., the ca. 2.0 Ga Laivajoki and Kortejärvi carbonatites).



Fig, 2a. Epsilon-Nd vs. age diagram for Palaeoproterozoic mafic rocks from the Taivalkoski (red triangles) and Pudasjärvi/ Peräpohja (blue diamonds) areas. Evolution lines are shown if the error in age is in excess of 20 Ma. The trend of the line follows typical composition of the rocks in the formation and the length of the line approximates the error in age. Also shown are the Kortejärvi and Laivajoki carbonatites, volcanic rocks from the Kuusamo belt (I= Kuntijärvi Fm, II =Petäjävaara Fm, III=Ruukinvaara Fm) and the evolutionary trend of a typical Neoarchaean granitoid (A1611).

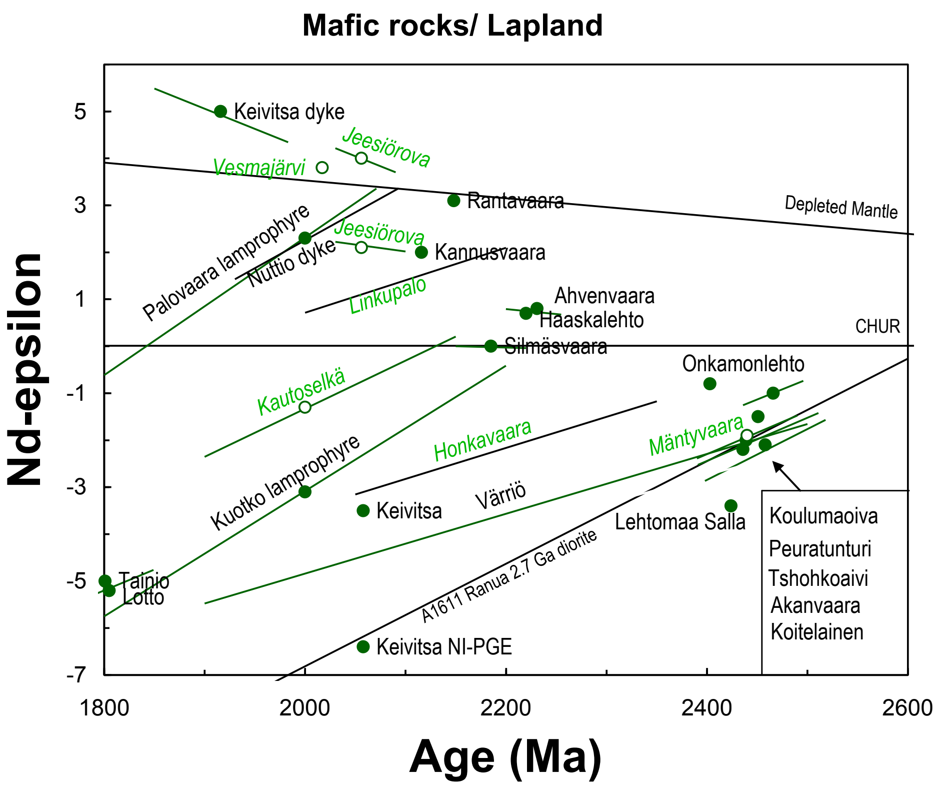


Fig. 2b. Epsilon-Nd vs. age diagram for Palaeoproterozoic mafic rocks from Lapland. Evolution lines are shown if the error in age is in excess of 20 Ma. The trend of the line follows typical composition of the rocks in the formation and the length of the line approximates the error in age. Volcanic rocks are labeled green. Also shown is the evolution of a typical Neoarchaean granitoid (A1611).

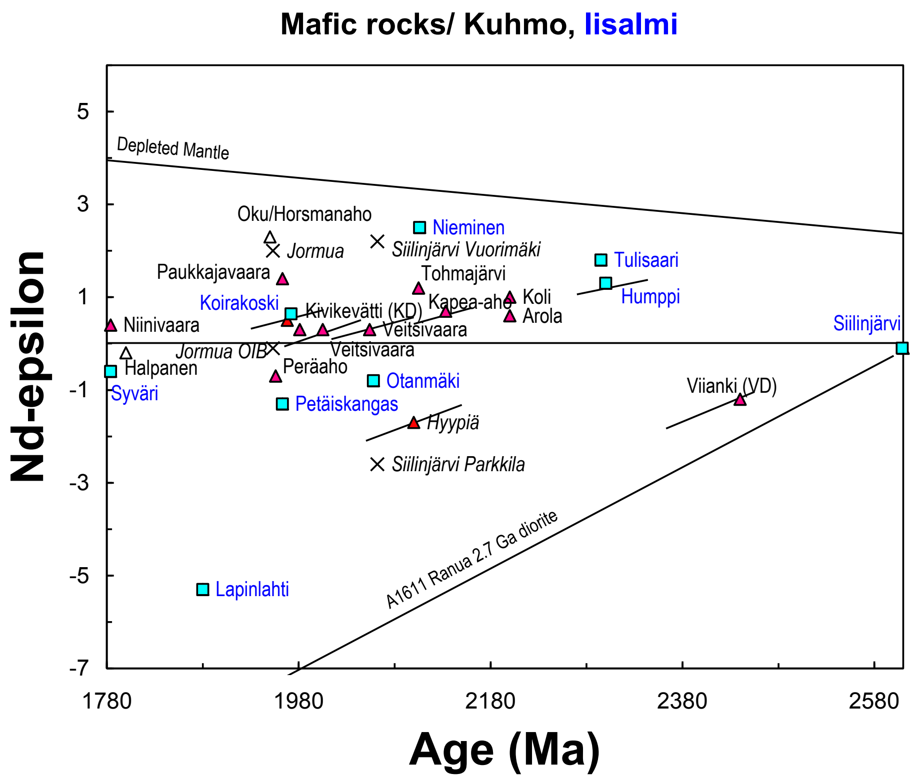


Fig. 2c. Epsilon-Nd vs. age diagram for Palaeoproterozoic mafic rocks from Kuhmo–Ilomantsi (red triangles) and Iisalmi (blue squares) blocks. Evolution lines are shown if the error in age is in excess of 20 Ma. The trend of the line follows typical composition of the rocks in the formation and the length of the line approximates the error in age. Also shown are ca. 1.95 Ga mafic rocks from Jormua and Outokumpu, ca. 2.06 Ga mafic volcanics from Siilinjärvi and Neoarchaean granitoid (A1611).

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THE AGE OF THE ARCHAEAN GREENSTONE BELTS IN FINLAND

by

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Reliable concordant U-Pb zircon data obtained using TIMS, SIMS and LA-MCICPMS methods for volcanic rocks in the Archaean greenstone belts in Finland indicate distinct age groups for each belt: Suomussalmi 2.94, 2.87 and 2.82 Ga; Kuhmo−Tipasjärvi 2.84–2.80 Ga; Ilomantsi 2.75 Ga; Kovero 2.88 and 2.75 Ga; Oijärvi 2.82–2.80 Ga; and NW-Lapland 2.93 and 2.84 Ga (Fig. 1). The relative abundance of rocks within these age groups still remains unclear. Results from the Kuhmo belt indicate that the age of felsic and gabbroic rocks in the central part of the belt (Kellojärvi area) is 2798 ± 2 Ma, which is also the minimum age for the local mafic-ultramafic magmatism, including komatiites. Tholeiitic mafic rocks in the Kuhmo belt, as represented by the Moisiovaara gabbro, are 2823 ± 6 Ma in age, which is considered the maximum age for the komatiites. Both the Kuhmo and Tipasjärvi belts contain sedimentary rocks that were deposited after 2.75 Ga, and thus at least 50 Ma after the volcanism. Still younger sediments have been found in the Arola area of the Kuhmo belt, where a deformed quartzite contains detrital zircon as young as 2.70 Ga. The sedimentary protoliths to the paragneiss belts were deposited at about 2.72 Ga.

Sm-Nd isotopic results show that volcanic rocks in the Kuhmo and Tipasjärvi belts mostly represent newly mantle-derived material (Fig. 2). The bulk of the granitoids surrounding the belt postdate the volcanic rocks, and the isotope results as a whole suggest that the contribution of older crustal material was negligible and does not support the existence of continental basement during the formation of the supracrustal rocks within these belts. In contrast, in the Suomussalmi belt, Sm-Nd and Pb isotope results indicate major involvement of significantly older crustal material (>3 Ga). A minor contribution of older crustal material is also evident in the Ilomantsi belt, where some igneous rocks contain xenocrystic

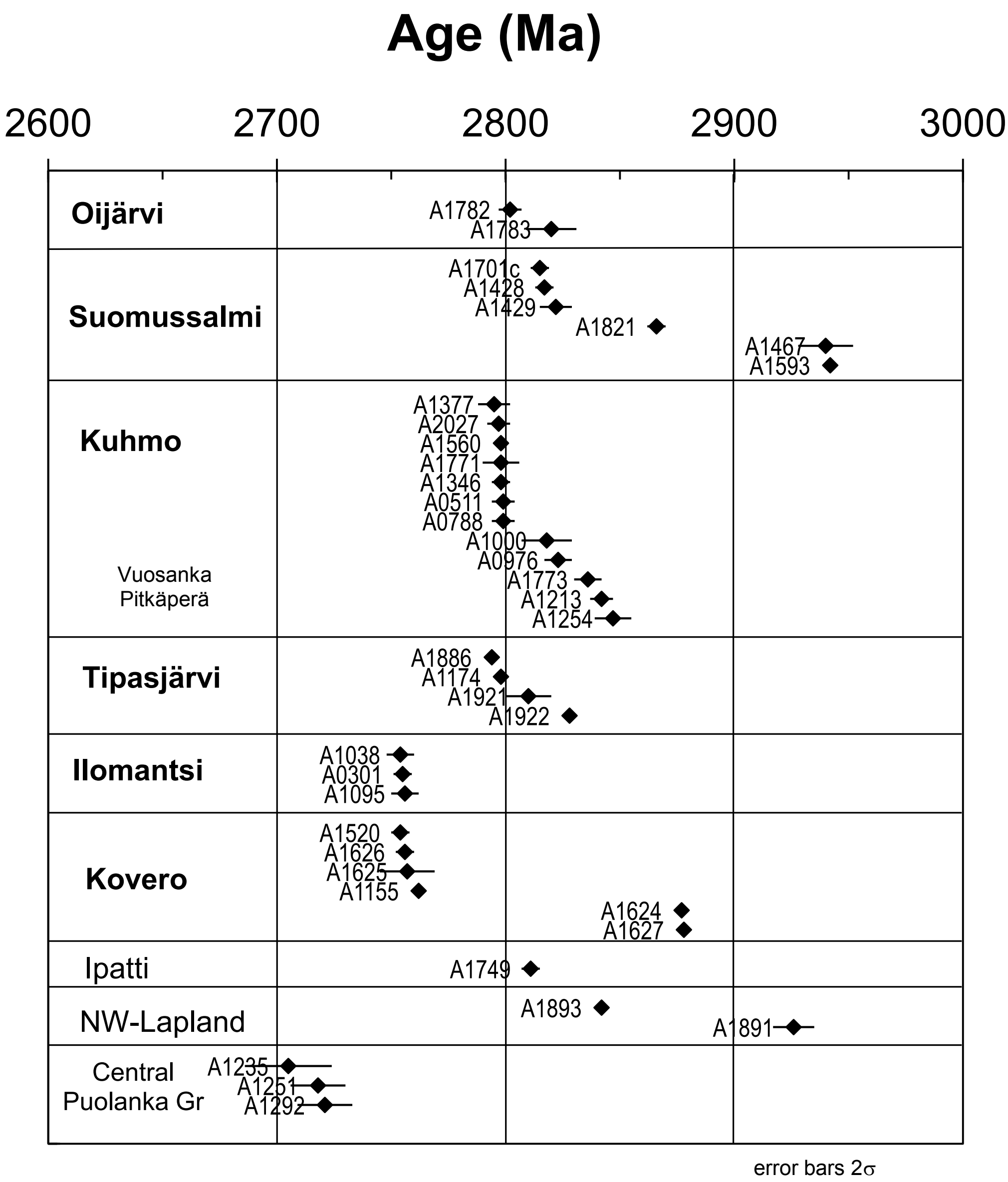

Fig. 1. U-Pb zircon ages for volcanic rocks from the Archaean greenstone belts in Finland, including samples from Ipatti belt and Central Puolanka Group.

zircon up to 3.3 Ga in age. Altogether, the isotope results suggest that the belts store a long-lived (>200 Ma), fragmentary record of geological evolution, possibly in various geodynamic settings, including an oceanic plateau (Kuhmo, Tipasjärvi), island arc (Ilomantsi), back arc/intra-arc (paragneiss belts) and intra-continental rift (Suomussalmi).

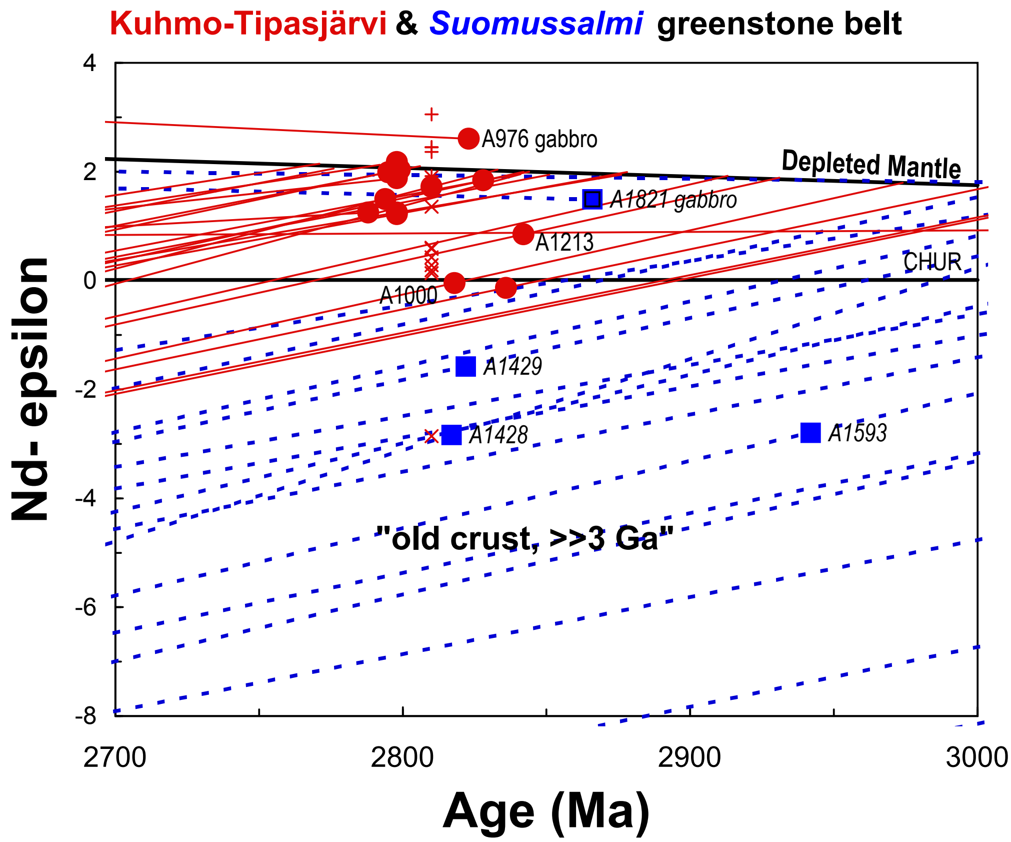

Fig. 2. Epsilon-Nd vs. age diagram showing evolution lines for mostly felsic samples from the Tipasjärvi–Kuhmo and Suomussalmi greenstone belts. Initial values are shown for samples, for which the age is based on U-Pb zircon dating. Suomussalmi: blue squares and dotted evolution lines. Kuhmo–Tipasjärvi: red circles and solid evolution lines. Komatiites and komatiitic basalts from the Pahakangas–Siivikkovaara area in Kuhmo: red x at 2810 Ma, basalts from other sites in Kuhmo belt: red +.

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TILL GEOCHEMICAL AND HEAVY MINERAL STUDIES IN HÄME BELT, SOUTHERN FINLAND

by

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Till geochemical and heavy mineral investigations in the eastern part of the Häme Belt represent a continuation of studies already undertaken in the western part of the Häme Belt (Kärkkäinen et al. 2012, Huhta et al. 2012, Sipilä et al. 2013) and commenced in early 2011, as part of the GTK project assessing the mineral potential of southern Finland. As of March 2012, 1153 till samples had been collected with GM50 or similar drilling equipment (Fig. 1). The sample points have been allocated to a 500x500 meter network according to till areas as shown on the Quaternary deposits maps.

The average depth of the samples is about three meters and the deepest are from over 15 meters. A total of 887 samples, with 41 elements per sample have been analyzed by Labtium from the till fine material (less than 0.06 mm). using the methods 515M, P, U; analytical difficulties at the beginning of the year 2011 led to re-analyzing 325 samples for gold.

It seems that best gold anomalies are in the contact zone between gabbros and volcanics but anomalous values are also found within the volcanics (Fig. 2).

Some of the gold anomalies detected have been confirmed with heavy mineral studies. Till samples weighing twenty kilograms have also been taken from 86 separate locations within the study area. Samples were enriched with the Gold-Hound spiral panner, and nuggets were calculated from samples using stereomicroscope. Nuggets were found in 38 samples (Fig. 2). The Susikas and Pirttikoski regions have been re-sampled. The sample points are along regular linear profiles or along roadsides at approximately 100 meter intervals.

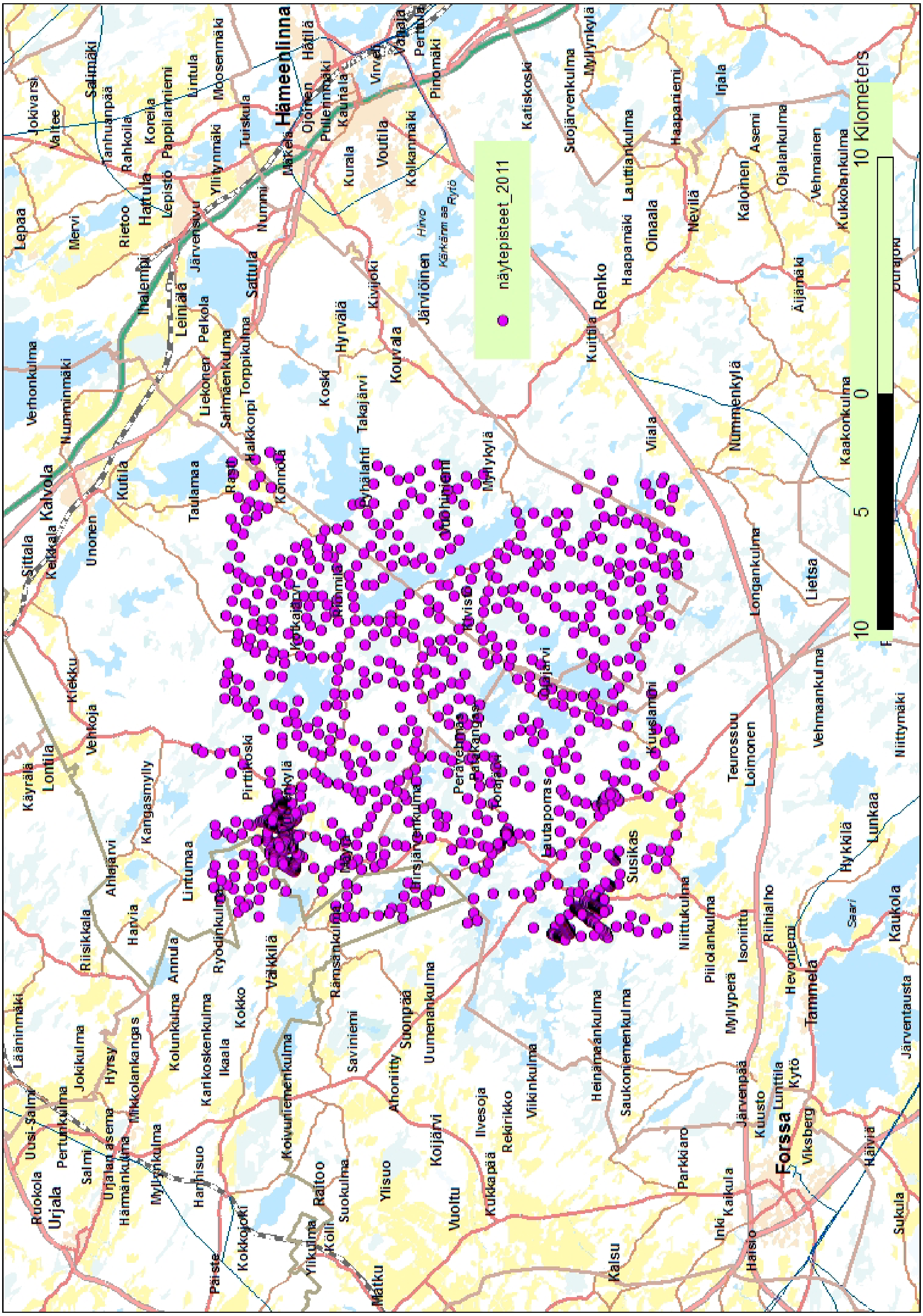

Fig. 1. Sampling points in eastern part of the Häme Belt between Forssa and Hämeenlinna. Contains data from the National Land Survey of Finland Topographic Database 2012.

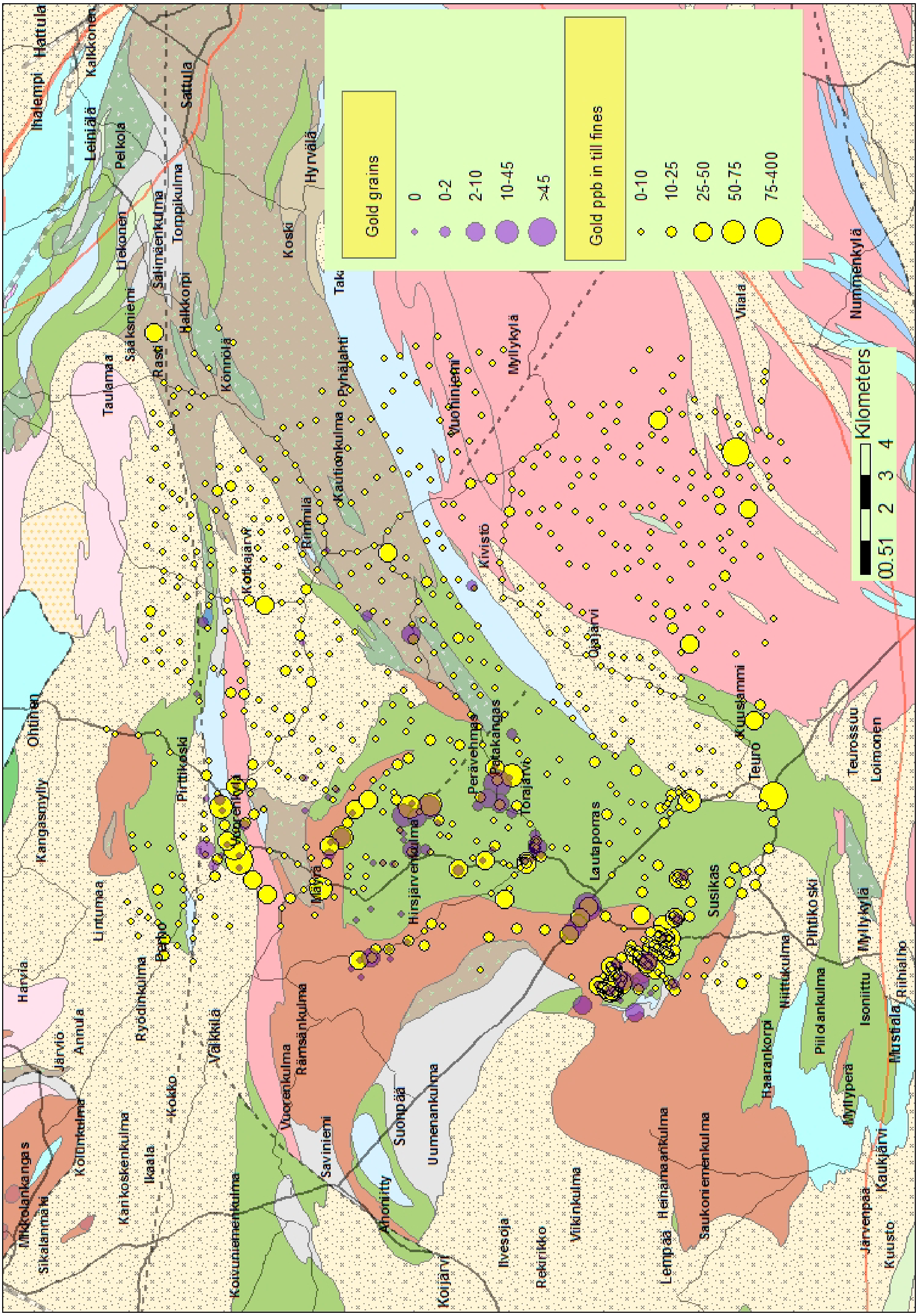

Fig. 2. Gold grains in heavy mineral samples and analyzed gold values in fine fraction of till. Contains data from the National Land Survey of Finland Topographic Database 2012.

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3D-MODELLING OF 2D IP MEASUREMENTS – EXAMPLES FROM GOLD PROSPECTS

by

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INTRODUCTION

The method of Induced Polarization (IP) has been one of the most widely used geophysical techniques in gold prospecting in recent decades. It has proven to be very effective in exploration for and delineation of disseminated ore types and also gives information about transition zones between barren and mineralized rock types. Surveys have usually been done with fast routine type systems where electrode separation is quite large, with only a few electrodes being deployed. When measuring with a small number of electrodes, the electrode separation increases with increasing depth penetration and the resolution of the measurement decreases.

Automatic electric imaging systems with IP mode have been tested at some gold prospecting sites with the intention of obtaining high resolution information about distribution of mineralization in the deeper parts of the bedrock. The depth penetration of the method is controlled by the maximum electrode spacing of the cables and type of electrode array deployed. A further aim of the research has been to progress towards 3D interpretation. Due to the ability to perform 3D-inversions of 2D results, it has now become possible to obtain 3D interpretations, requiring very little additional work compared to that needed for 2D-inversion.

MEASUREMENTS

The first test measurements were done in the Seinäjoki region in the autumn of 2007 using ABEM Terrameter SAS4000 equipment with a Lund Imaging System (see Fig. 1). The following year the testing was continued at another site near Seinäjoki. In 2009 the measurements were done in the Forssa–Jokioinen region.

The SAS 4000 and Lund Imaging System represents a 4-channel multi-electrode electric imaging system. It includes 4 cables with 21 take-out points every 5 meters, allowing measurement of 81 electrodes in one spreading of a profile. With 5 meters minimum electrode spacing the length of one spreading is 400 m. The equipment can operate in three different modes: resistivity, IP and also self-

Fig. 1. ABEM Terrameter SAS 4000 with Lund Imaging System (ABEM Instrument AB 2012).

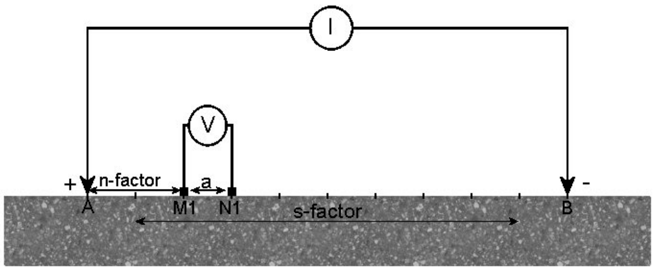

Fig. 2. Multiple-gradient array.

potential mode. For the surveys made at the gold prospects, the multiple gradient electrode array was used. The multiple-gradient array represents a form of combined pole-dipole and Schlumberger electrode arrays (see Fig. 2).

MODELLING AND VISUALISATION

The interpretation of the 2D measurement results was done using the Res3DInv program (Geotomo Software 2011). The visualisation of the inversion results is usually made using Geosoft Oasis Montaj. Figure 3 shows an example of the 3D-inversion interpretation result from the gold prospecting target in Seinäjoki area, measured 2008.

CONCLUSIONS

The advantage of the multi-electrode electric imaging system is the higher data resolution compared to IP measurement systems previously deployed GTK surveys. On the other hand, the speed of measurement is quite slow in comparison to traditionally used systems; accordingly the multi-electrode method could be

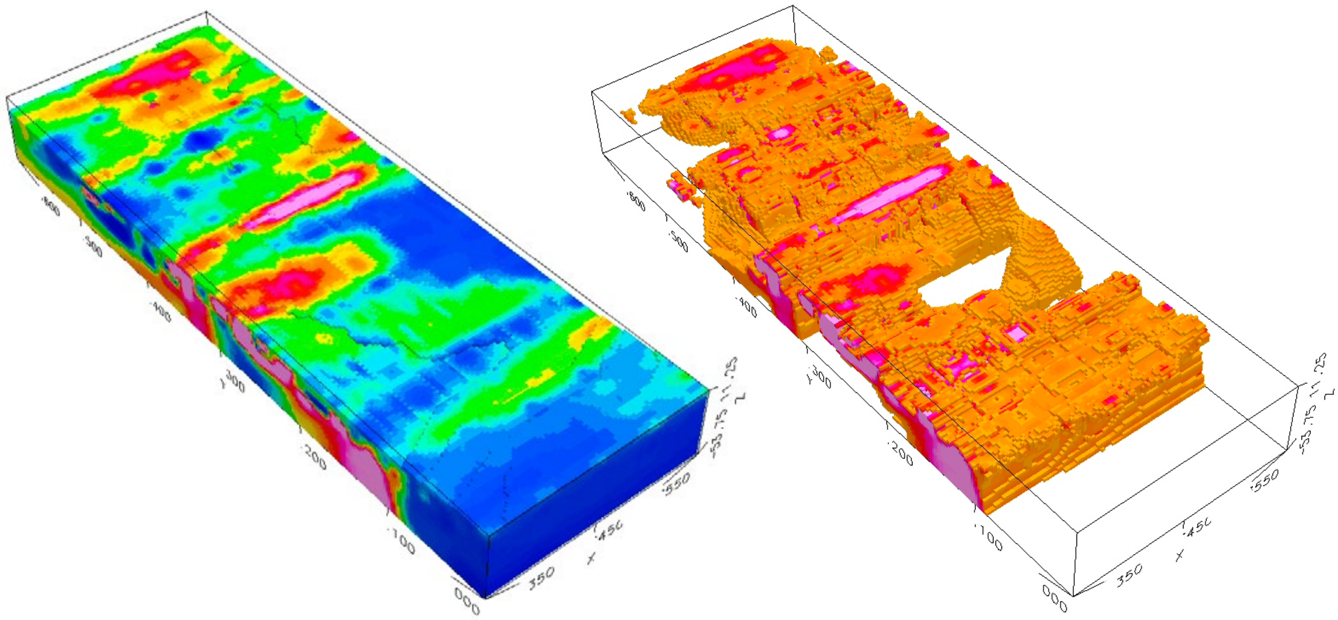

Fig. 3. 3D IP inversion result from Seinäjoki area, measured in 2008. In the image on the right hand side, values over 30 msec are defined.

recommended for more detailed surveys, after firstly defining the measurement grid on the basis of regional IP results.

The results of trial surveys in the three different test areas showed that 3D-interpretation is a valuable addition to 2D interpretation. In the 3D-inversion the 3D sources in the 2D data can be interpreted, because the data from the neighbouring profiles is taken into account.

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AIRBORNE GEOPHYSICAL, PETROPHYSICAL AND GEOCHEMICAL CHARACTERISTICS OF PALAEO-PROTEROZOIC BLACK SHALE UNITS IN FINLAND: APPLICATIONS FOR EXPLORATION AND ENVIRONMENTAL STUDIES

by

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Palaeoproterozoic black shales in Finland are easy to recognize on aerogeophysical maps. They have distinct geophysical properties, such as electrical conductivity and magnetization, enabling stratigraphically constrained units with high concentrations of graphite and sulphides to be followed for tens to hundreds of kilometers. Therefore, a combination of airborne magnetic and electromagnetic survey data can be used for the identification of black shale units and mapping their regional distribution (Arkimaa et al. 1999, 2000). Airborne geophysical, geochemical and petrophysical data have been collected for detailed interpretation in order to characterize different black shale units in Finland. Altogether 800 black shale samples from drill cores all over the country were selected (Loukola-Ruskeeniemi et al. 2011). All drill cores from which graphite or black shale had been reported, were also reinvestigated for the purpose of this comparative black shale study.

The petrophysical properties of black shales depend on their mineral composition and the abundance of graphite and sulphides in particular, with considerable differences being observed from site to site (Airo & Loukola-Ruskeeniemi 2004). The mean density for "average" black shale is about 2800 kg/m^3 where graphite reduces and sulphides increase the density. Mean susceptibilities are about 6000 x10^{-6} SI-units and depend directly on the abundance of ferrimagnetic pyrrhotite. Consequently, the intensity of remanent magnetization is about 3 A/m. Königsberger ratios (the ratio of remanent to induced magnetization) for ordinary black shales range between 10–100, which allows effective discrimination between pyrrhotite-bearing source rocks and magnetite-bearing rocks, in which Königsberger ratios are typically below 5. Black shales are highly conductive and resistivity values are mainly below 1 Ohm-m.

Even though black shales are easy to identify in airborne geophysical data, their interpretation is challenging; geophysical properties vary within individual

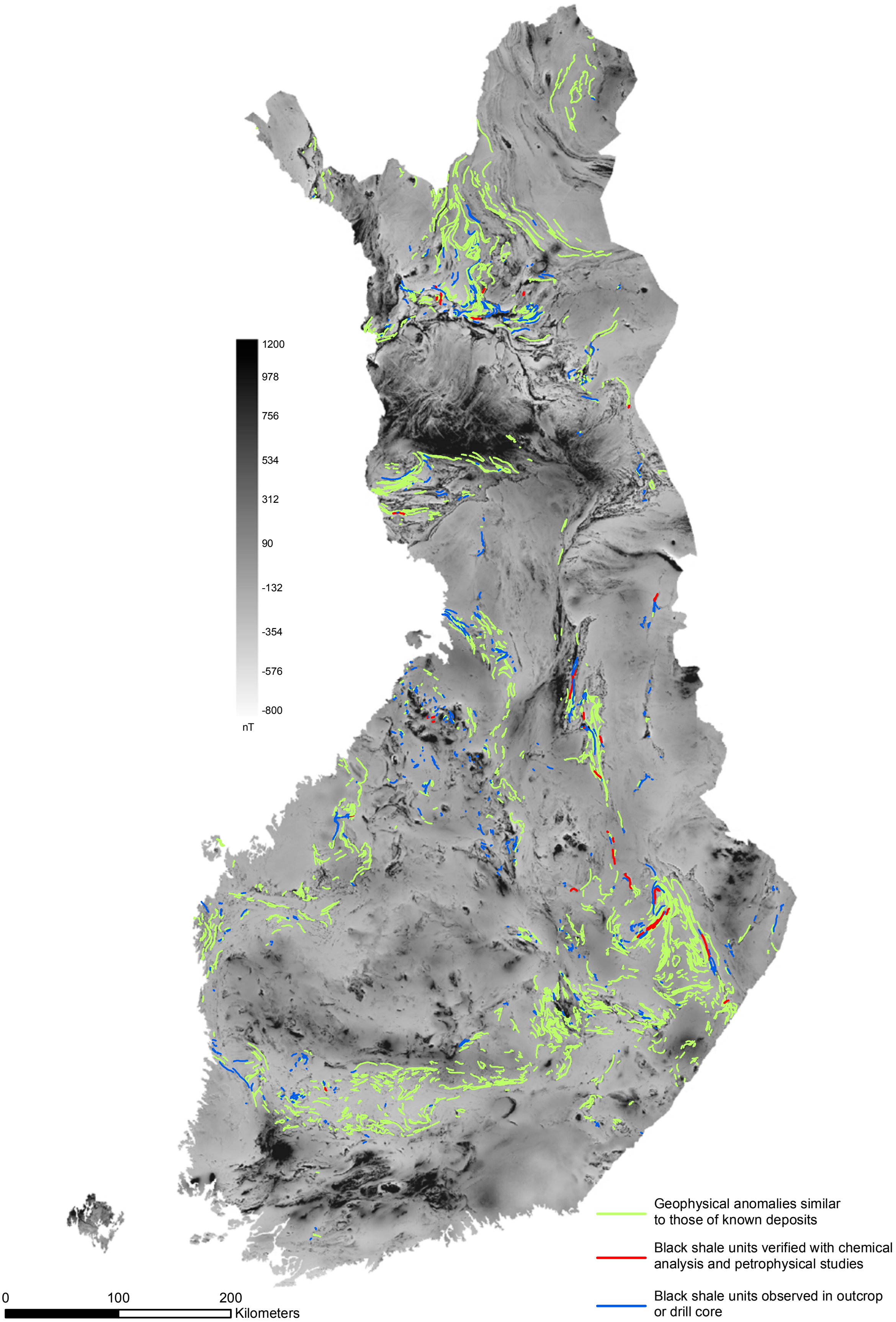

Fig. 1. Preliminary distribution of black shale units on a low-altitude airborne total intensity magnetic map. Red lines indicate the presence of black shale units, confirmed by chemical analysis and petrophysical studies. Blue lines indicate black shale units observed in outcrops or drill cores. Green lines represent potential black shale units, interpreted from low-altitude airborne data.

lithostratigraphic units and the measured responses are controlled by bedrock geology and structure, overburden and conductivity structures. Variation in the concentrations of C, S and Fe clearly affect the geophysical responses. Increased S abundances in geochemical data can be correlated with increased conductivity and consequently for C~10% the concentration of Fe decreases considerably. This affects the composition and abundance of the Fe sulphides– there is a linear correlation between magnetic susceptibility and the abundance of monoclinic pyrrhotite. Aeroradiometric data can be used to estimate the effects of alteration and weathering associated with mineralization.

The map of Palaeoproterozoic, metamorphosed sedimentary rocks rich in organic C and S was compiled by correlating aeromagnetic and aeroelectromagnetic data (Fig. 1). The inferred black shale units were verified with chemical analyses and petrophysical studies of drill core samples. Statistical analysis and interpretation of airborne geophysical, geochemical and rock petrophysical data are used to characterize and classify black shales in Finland and the results are compiled in the black shale database which is designed to be part of the Bedrock of Finland – DigiKP –database. These results provide background constraints for both mineral exploration and environmental studies. Black shales can cause environmental problems (e.g. Loukola-Ruskeeniemi et al. 1998) and drilling a well into black shale bedrock for groundwater is not recommended.

Metamorphosed black shales in Finland have long been known for their ore potential. The Talvivaara deposit contains more than 1550 Mt of Ni-Cu-Co-Zn-Mn-U ore and was deposited in a stratified marine basin 2.0–1.9 Ga ago (Loukola-Ruskeeniemi & Heino 1996, Kontinen, 2012). High concentrations of organic C and S similar to those in the Talvivaara deposit occur in many localities in eastern and northern Finland, but Ni, Cu, Co, Zn, and Mn concentrations were lower in the present sample set, represented by 800 samples from throughout Finland. Indications of high Pd abundances were noted from some prospects, whereas U-rich black shale units were not encountered.

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SVECOFENNIAN METAMORPHISM IN POHJANMAA, WESTERN FINLAND

by

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Metamorphism reflects the tectonic evolution of the bedrock; e.g. in modern plate tectonic regimes high pressure metamorphic rocks (blueschists, eclogites) are found in subduction zones, medium pressure Barrovian style rocks in collisional orogens and low pressure-high temperature rocks in magmatic arcs. Compilation of a metamorphic map of Finland is being undertaken at GTK for use in geodynamic modeling and predicting zones that have potential for metamorphogenic ore deposits. In 2011 field work was done in the Pohjanmaa area in western Finland.

According to currently available data, almost all metamorphosed Svecofennian rocks in southern and central Finland represent low pressure-high temperature metamorphism, most areas having been metamorphosed at pressures of 4-6 kbars, corresponding to inferred crustal depths of about 11–16 km (Korsman 1977, Korsman et al. 1984, Schreurs & Westra 1986, Hölttä 1988, 1995, Mouri & Korsman 1999, Mouri et al. 1999, Väisänen & Hölttä 1999, Mäkitie 1999, 2000, Mäkitie et al. 2001). On the basis of field observations, the Pohjanmaa area does not appear to be different; metasedimentary rock units in Pohjanmaa are characterized by strong metamorphic zoning from mid-amphibolite facies schists to granulite facies diatexitic migmatites towards the Vaasa granitoid complex, a structure resembling a metamorphic core complex. The lower grade zone extends along the western margin of the Central Finland Granitoid Complex from the Seinäjoki area to Ylivieska. Metasediments in this area are schists, with no signs of migmatisation. Rocks with peraluminous compositions have the mineral assemblages bt-ms-qtz±and±sil±pl, bt-st-chl-qtz, bt-ms-crd-qtz±and±sil±pl, bt-ms-st-grt-chl-qtz, bt-ms-grt-qtz±and±sil, bt-ms-st-qtz±sil and bt-crd-st-chl-pl-qtz±grt. Where cordierite and staurolite occur in the same assemblage cordierite is often the breakdown product of staurolite, indicating decreasing P and/or T. The dip of schistosity in andalusite-grade schists is generally near vertical whereas in migmatites the deformation style is more variable, also showing subhorizontal planar structures.

With the increase in metamorphic grade towards the Vaasa granitoid complex, peraluminous metasediments have become sillimanite gneisses. Grain size coarsens and gneisses often have small amounts of neosome, indicating the onset of incipient melting, with mineralogy characterized by the assemblage is bt-ms-pl-qtz±sil±kfs. Sillimanite is commonly crystallized on muscovite rims, indicating the reaction ms+qtz=kfs+sil. Sillimanite gneisses are transitional to metatexitic and diatexitic garnet-cordierite migmatites which have the mineral assemblage bt-grt-crd-pl-qtz±sil±kfs±and±ky±st. Andalusite, kyanite and staurolite are retrograde minerals after cordierite, occurring as small grains. The presence of retrograde kyanite in many samples indicates near-isobaric cooling paths.

In the NE part of Pohjanmaa there is another large migmatite terrain. In the Kiiminki area at the boundary of the Archaean craton mid-amphibolite facies schists predominate although their metamorphic evolution, seems to differ from that of the schists in SW Pohjanmaa. Typically, the Kiiminki schists lack porphyroblasts but at Ylikiiminki there are exposures where the mineral assemblages are bt-st-and-grt-qtz±ms, bt-st-grt-crd-qtz ±and±chl±ms±pl, bt-st-grt-chl-qtz, bt-ms-chl-crd-grt-qtz±st. Andalusite, staurolite and cordierite seem to be in textural equilibrium forming the early phases but euhedral garnet overgrows all minerals, being a late phase and indicating increasing pressure.

Another locality where metamorphism differs from the general low-P type is at east of Vimpeli. Within a small area of possibly only a couple of square kilometers, gneisses were found containing the assemblage bt-ms-ky-chl-pl-qtz , in which kyanite forms large euhedral large prisms as though being a prograde mineral. This area probably represents a tectonic sliver of deeper crust.

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NEW U-PB ZIRCON AGE, SM-ND ISOTOPE AND GEOCHEMICAL DATA FOR OTANMÄKI SUITE GRANITES IN THE KAINUU AREA, CENTRAL FINLAND

by

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A fault-bounded, 1–8 km wide, boomerang-shaped body of Proterozoic peralkaline to peraluminous A-type granites extends 65 km from Otanmäki (W) via Lehtomäki and Soidinvaara to Kuluntalahti (E) in the area south of the Oulunjärvi lake, in central Finland (Fig. 1). These Otanmäki suite granites (OSG) are of particular interest because of their proximity to the Jormua ophiolite (1.95 Ga), and within this context, their chemical affinities with the A-type granites emplaced in conjunction with the opening of the Red Sea 30–20 Ma ago. Furthermore, the peralkaline granites host prospects with economically interesting REE contents and the peraluminous granites are associated with minor pyrometasomatic Fe±Ag±Mo enriched skarns where in contact with carbonate rich country rocks.

The OSG are invariably moderately to strongly deformed, and typically show gneissic-foliated textures, attesting to their pre-tectonic (pre-Svecofennian) emplacement. The N and S contacts of the granite boomerang, both of which are with Archean gneissic rocks, appear very sharp, and are probably fault-defined. Moreover, no occurrences of Otanmäki type granites are known outside of the boomerang-shaped area. However, the pervasive intrusion of 1.80 Ga Kajaani granite-pegmatite dikes throughout much of this area has somewhat obscured relationships amongst the older rocks. In the west, dikes of OSG intrude the 2.06 Ga Otanmäki layered gabbro and a suite of banded quartz-feldspar gneisses having chemical compositions quite similar to those of the OSG. The quartz-feldspar gneisses may represent sub-volcanic and/or volcanic rocks cogenetic with the OSG, although they have previously been interpreted as psammitic rocks metasomatised by OSG-derived alkaline fluids.

In the western part of the granite boomerang, in the Otamäki area, the OSG are typically peralkaline and mostly alkali-amphibole±aegirine bearing granites, whereas in the east they are mostly peraluminous muscovite-biotite granites (cf. Fig. 2). A high abundance of zircon and the frequent occurrence of fluorite grains are characteristic minor features for both the peralkaline and peraluminous granites. As mentioned above, and first noticed by Peltonen et al. (1996), the OSG have major and trace element chemical compositions similar to those of A-type granites emplaced during the initial opening phase of the Red Sea. For example,

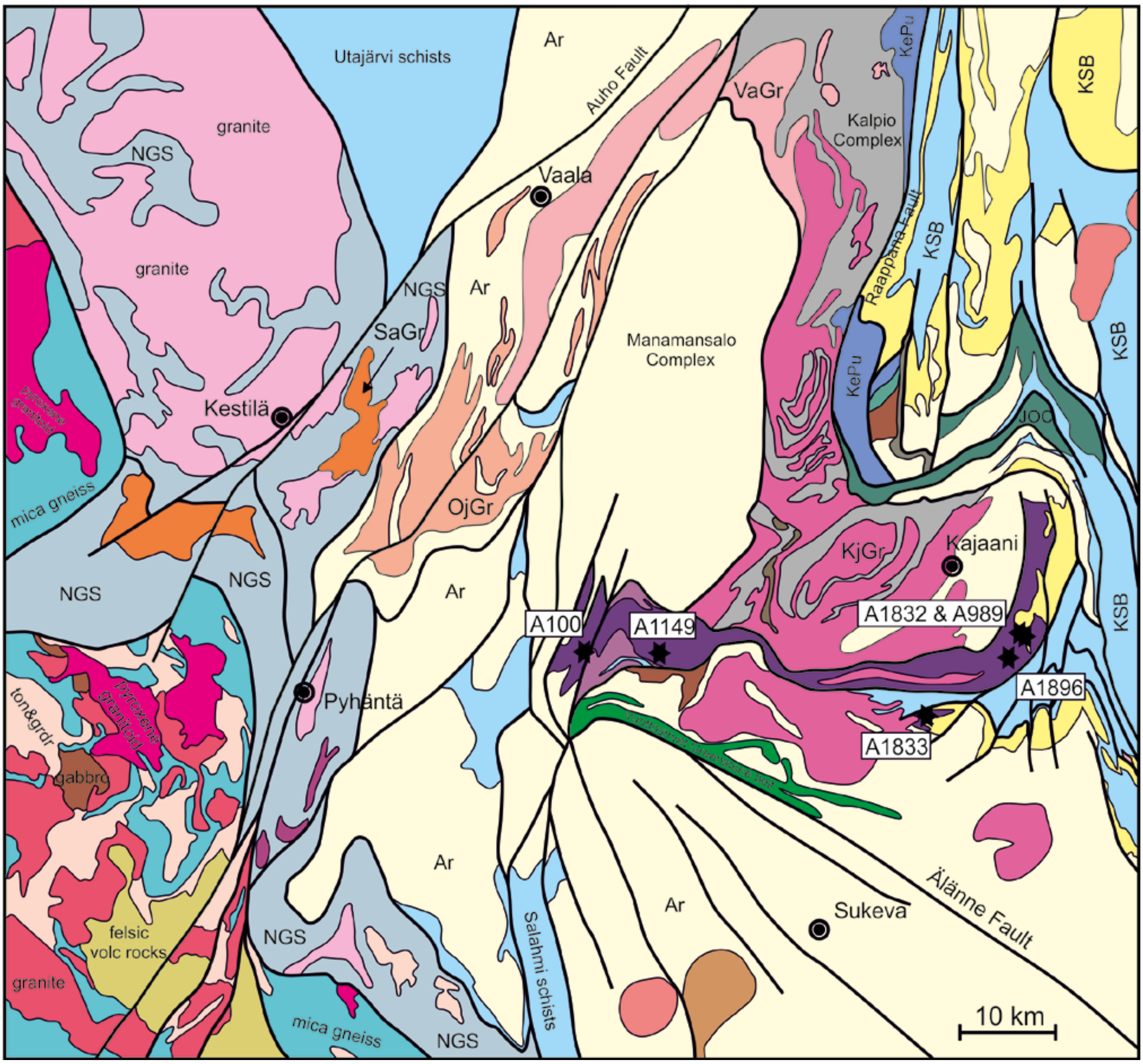

Fig. 1. Generalized geological map showing regional setting of the Otanmäki granite suite (dark violet color) and locations of samples selected for U-Pb zircon dating/re-dating in this study. Ar=Archean rocks, NGS=Näläntöjärvi Gneiss Suite, KePu=Keski-Puolanka Group, JOC=Jormua Ophiolite Complex, KjGr=Kajaani granite. Jatuli (2.3–2.1 Ga) and Kaleva stage (2.1–1.9 Ga) rocks of the Kainuu Schist Belt (KSB) are shown by yellow and light blue, respectively.

they display a similar range from peralkaline to peraluminous compositions on the A/NK versus A/CNK diagram (Fig. 2). Another feature in common with the Red Sea granites is that the Otanmäki suite granites plot as within-plate /A1 types on granite discrimination diagrams (Fig. 3).

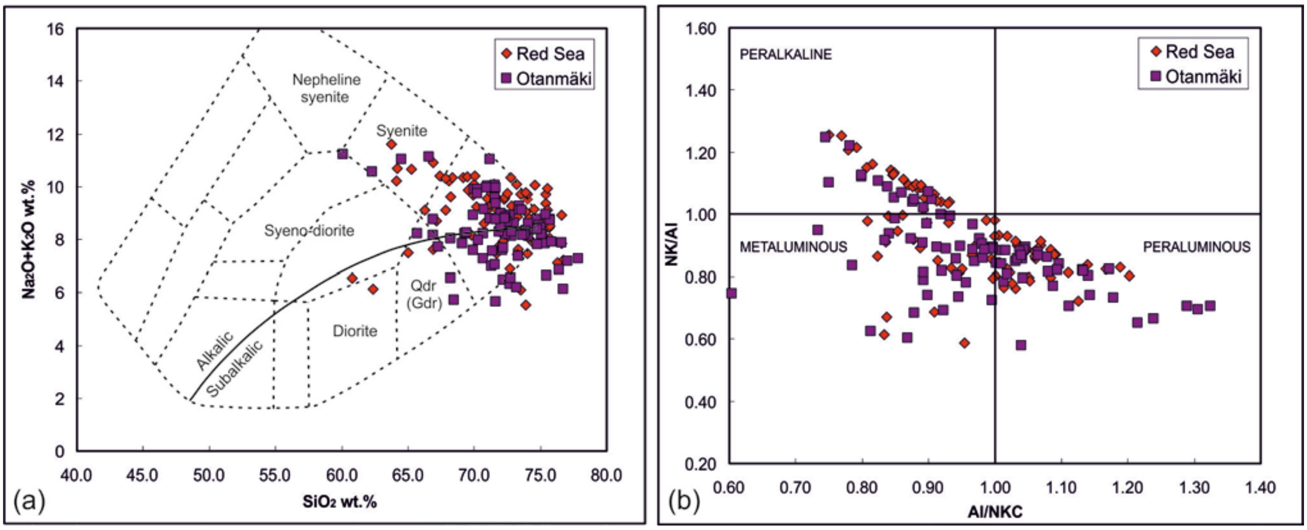

Fig. 2. (a) Na2O+K2O versus SiO2 and (b) (Na2O+K2O)/ Al2O3 versus Al2O3/(Na2O+K2O+CaO) (molar) diagrams for Otanmäki suite and for comparison Red Sea 30-20 Ma granites and related felsic volcanic rocks (Coleman et al. 1992, Tommasini et al. 1994).

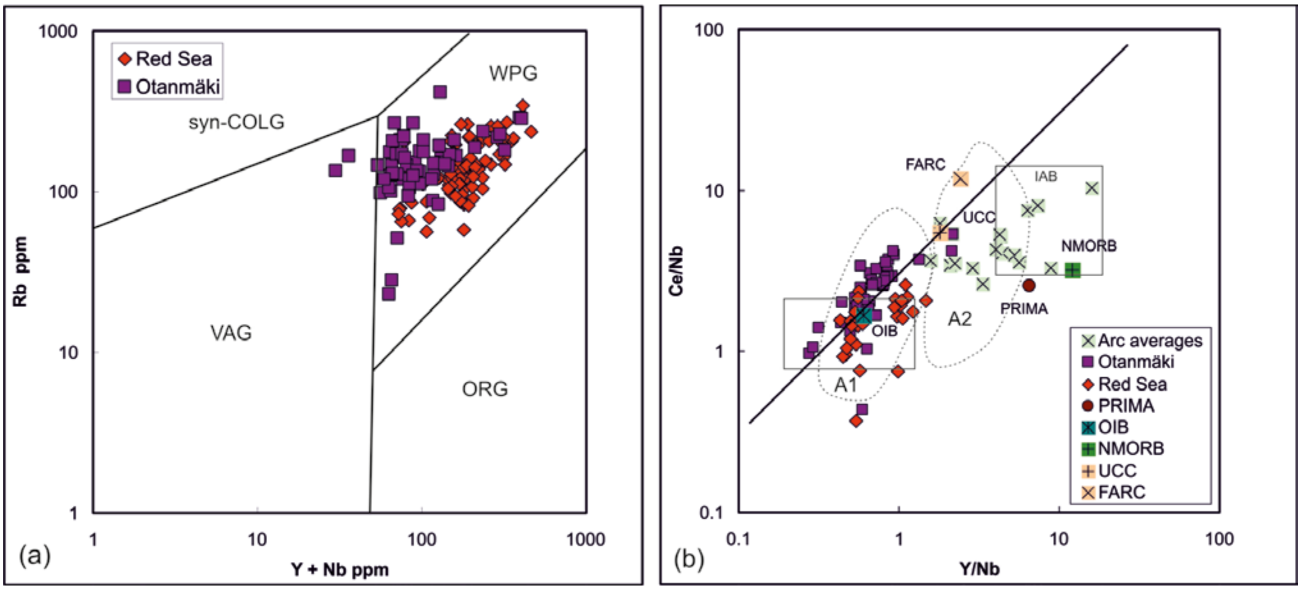

Fig. 3. (a) Rb versus Y+Nb and (b) Ce/Nb versus Y/Nb diagrams for samples from Otanmäki suite and for comparison Red Sea 30-20 Ma granites and related felsic volcanic rocks (Coleman et al. 1992, Tommasini et al. 1994). Discrimination fields in (a) from Pearce et al. (1984) and (b) after Eby (1990). Syn-COLG=syn-collisional granite, WPG=within plate granite, VAG=volcanic arc granite, ORG=ocean ridge granite, PRIMA= primitive mantle, OIB=ocean island basalt, IAB=island arc basalt, A1/A2-type granite, NMORB=average N-type mid-ocean ridge basalt, UCC=average upper continental crust, FARC=average Finnish Archaean crust.

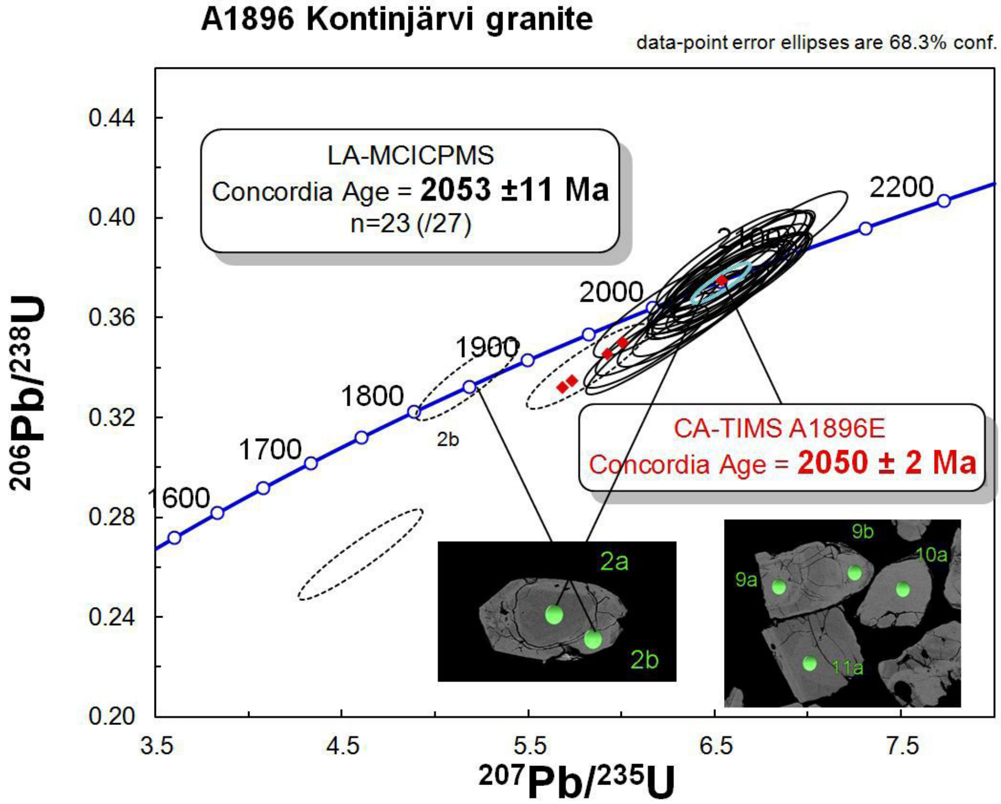

Fig. 4. Concordia diagram showing TIMS multi-grain (red diamonds) and LA-ICP-MS spot analyses (error ellipses) for zircons from the granite sample A1896 Kontinjärvi (cf. Fig. 1). Concordant analyses by TIMS and LA-ICP-MS from grain cores are consistently close to 2050 Ma, which is interpreted as the probable crystallization age of the Kontinjärvi granite. Grain margins tend to yield also discordant and/or younger analyses, reflecting metamorphic effects.

Conflicting views on the magmatic age of the OSG have been presented in the past. An age of about 2050 Ma was proposed by Marmo at al. (1966) and 1960 Ma by Peltonen et al. (1996), both views being based on multigrain TIMS zircon dating; in the case of Marmo et al. (1966) for a sample from the Otanmäki area (A100) and in the case of Peltonen et al. (1996) for samples from Otanmäki (A1149) and Soidinvaara (A989). In order to clarify the age problem, all previously studied samples, along with four new ones from OSG have been/will be studied for their zircon ages by the CA-TIMS (Mattinson 2005) and LA-ICP-MS. The new data indicate an age of c. 2050 Ma for the magmatic age of the peraluminous end member. Individual results include 2050±2 Ma by CA-TIMS for sample A1896 from Kontinjärvi, concurring with an identical 2053±11 Ma by LA-ICP-MS (Fig. 4). Work on the magmatic age of the peralkaline end member is still in progress but one of the previously analyzed samples, A1149 Otanmäki, has already been reanalyzed by LA-ICP-MS.This sample turned out to have a bimodal population with concordant single-spot data for "good-looking" grains producing an age of 2049±10 Ma and "bad-looking" zircon grains/domains ranging from 1960 to 1830 Ma. We tentatively interpret 2049±10 Ma as the magmatic age with the younger data reflecting some yet unspecified post emplacement alteration event. Thus an age of about 2050 Ma, as was first proposed by Marmo et al. (1966), seems likely also for the peralkaline OSG. It is however noteworthy that the new laser data explain the 1.96 Ga TIMS age previously obtained for multigrain splits of zircon grains from sample A1149.

Sm-Nd isotope data obtained for nine representative samples of the OSG give ε_{Nd} (2050 Ma) values that range from -3.1 to +0.7. We interpret these data, combined with trace element distributions (Fig. 3), to indicate an OIB type plume mantle source for the OSG and variable contamination during magma ascent through lithosphere and extended/faulted continental crust, possibly in a similar tectonic setting to that during the opening of the Red Sea, as was proposed by Peltonen et al. (1996). However, the new age data imply the OSG was emplaced up to 100 Ma earlier than was believed by Peltonen et al. (1996). This would require an exceptionally slow/protracted/intermittent development from the first stages of rifting at 2.05 Ga to full break-up and initiation of oceanic crust formation at 1.95 Ga when the Jormua-Outokumpu ophiolites formed. Alternatively, the ophiolites and their host "Upper Kaleva" turbidites could represent entirely exotic components with respect to the Karelian craton margin. An exotic allochthonous origin may be invoked also for the OSG, noting their occurrence in a well-defined zone that could easily be interpreted as a solitary tectonic sliver. However, the root of this Otanmäki sliver would seem to have been within the (at 2050 Ma) rifted craton margin, an inference which is supported by the presence of "marine Jatuli" type quartzitic-dolomitic rocks within the granite sliver, and occurrences of similarly aged (2050 Ma) and thus possibly cogenetic alkaline mafic-felsic units as the OSG elsewhere along the craton margin, for example at Siilinjärvi and Yli-Tornio, suggesting an essential genetic relation between this magmatism and the evolution of the craton margin.

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NEW U-PB ZIRCON AGE, SM-ND ISOTOPE AND GEOCHEMICAL DATA ON PROTEROZOIC GRANITIC ROCKS IN THE AREA WEST OF THE OULUNJÄRVI LAKE, CENTRAL FINLAND

by

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The gneiss-granite dominated area to the west of the Oulunjärvi Lake, between the Svecofennian domain and Kainuu Schist Belt, has seen relatively little geologic research since the pioneering work of Wilkman (1931). We have recently reviewed this long ignored area through both field and laboratory studies. The bedrock in the area comprises banded-migmatitic, presumed Archaean TTG gneisses in the east (near the Oulunjärvi Lake) and migmatitic, amphibolite-intercalated mica gneisses of the Palaeoproterozoic Näläntöjärvi Suite in the west (in the Kestilä area, Fig. 1). This gneissic framework is intruded by abundant younger granites that belong to several distinct suites.

We have focused on the three apparently youngest and also most voluminous of the granite suites, designated here as the: (1) Vaala, (2) Oudonjärvi and (3) Salmineva granites. The Vaala and Oudonjärvi granites occur in the east within the Archaean TTG gneisses, whereas the Salmineva granites seem to be restricted to the west, within the Proterozoic Näläntöjärvi Suite (Fig. 1). In outcrop all these granites are typically grey to pink, and relatively leucocratic, medium- to coarse-grained granodioritic to granitic rocks. The Vaala granites are poorly exposed, Oudonjärvi granites typically occur as dykes from several metres to hundreds of metres in width that sharply truncate structures in the host gneisses whereas Salmineva granites apparently occur as larger plutons, locally containing angular inclusions of foliated monzogabbro-monzodiorite. The Vaala granites and in particular the Oudonjärvi granites are predominantly well-foliated whereas the Salmineva granites considerably vary in this respect. Rock textures are usually even-grained and foliated although the Vaala and Salmijärvi granites also include K-feldspar-phyric variants. The Vaala granite typically contains magnetite, while the Oudonjärvi granite varies in this respect and the Salmineva granites generally lack magnetite. A distinct feature of all these granites is the ubiquitous presence of minor but readily discernible amounts of altered allanite.

Representative samples of the three granite suites have been studied for their zircon U-Pb ages, Sm-Nd isotope and major and trace element geochemistry.

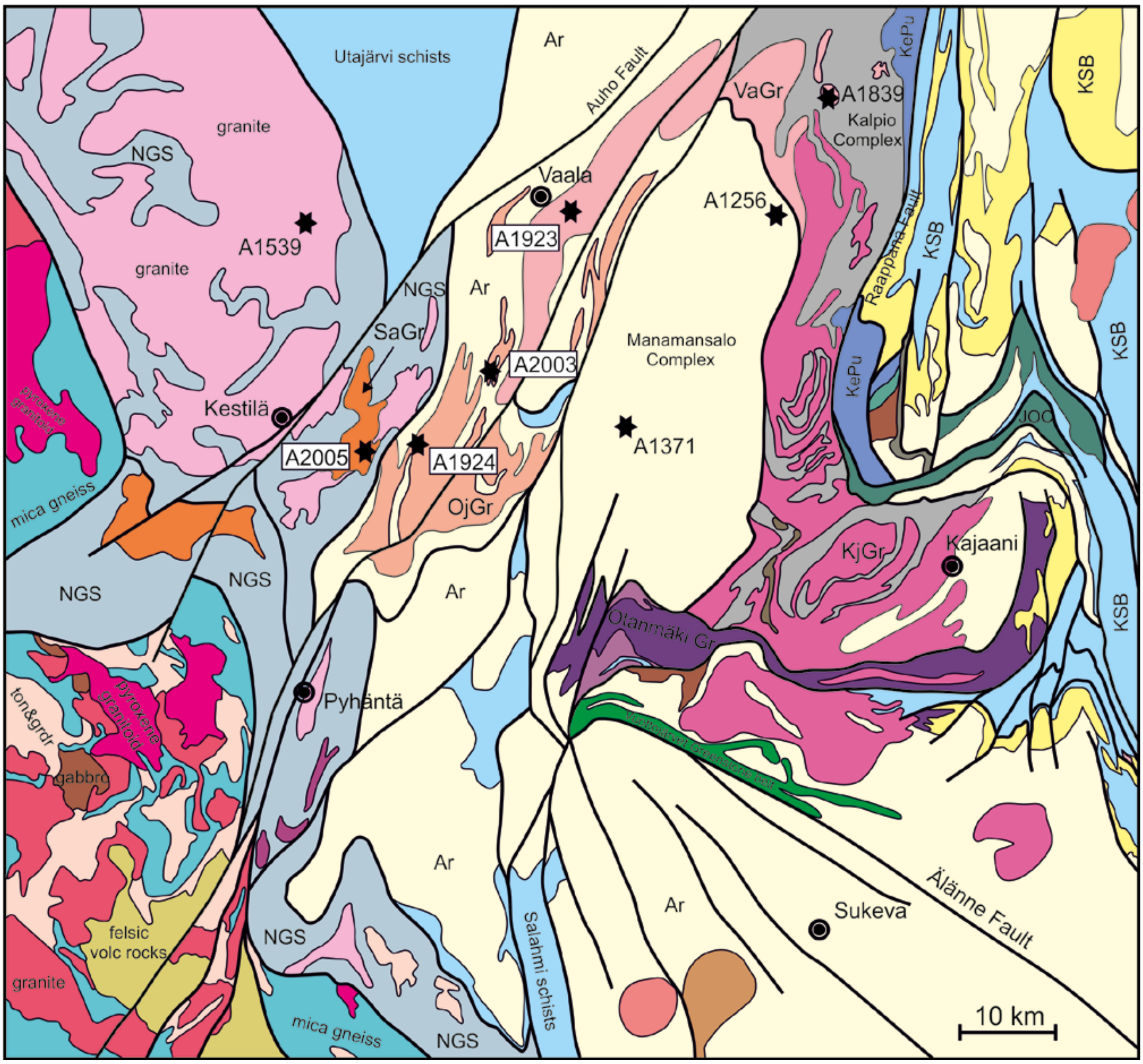

Fig. 1. Generalized geological map showing regional setting of the studied Vaala (VaGr), Oudonjärvi (OjGr) and Salmineva (SaGr) granites. Locations of zircon (U-Pb) dated samples are shown by the A-lettered numbers in white boxes. The unboxed A-lettered numbers refer to previously dated samples (TIMS) interesting in the present context: A1256/1795±5 Ma, Vaala granite/dyke (Vaasjoki et al. 2001); A1371/1874±6 Ma, diorite/dyke /GTK unpublished); A1539/1784±2 Ma (monazite), granite (Kousa & Luukas 2007), A1839/1787±6 Ma, Vaala granite/small stock (GTK unpublished). Ar=Archean rocks, NGS=Näläntöjärvi Gneiss Suite, KePu=Keski-Puolanka Group, KSB=Kainuu Schist Belt, JOC=Jormua Ophiolite Complex, KjGr=Kajaani granite.

The Vaala granites are relatively high in SiO_2 (67.5–73.7 wt.%), K_2O+Na_2O (8.25–8.61 wt.%), K_2O/Na_2O (1.41–1.85), Th (36–74 ppm), LREE (La 98–268 ppm), Zr (291–611 ppm) and show deep negative Eu minima in their mantle normalized trace element patterns. Compared to Vaala, Oudonjärvi granites show somewhat wider variability in SiO_2 (64.0–72.9), are lower in K_2O+Na_2O (6.75-8.42) and K_2O/Na_2O (0.32–1.60), have less prominent Eu negative anomalies and have mostly somewhat lower Th (11–34 ppm), LREE (La 35–119 ppm) and Zr (181–434 ppm). Both Vaala and Oudonjärvi suites are characterized by low Nb/La (0.04–0.32) and Nb/Th (0.09–1.15). The Salmineva suite shows the

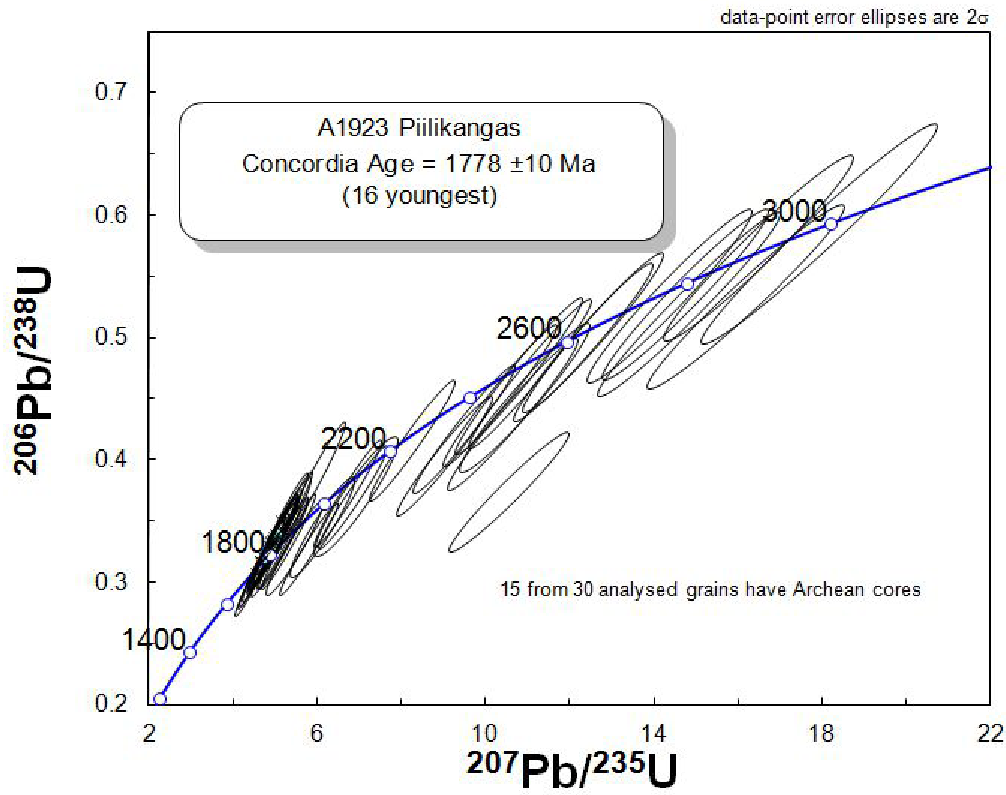

Fig. 2. Concordia diagram of La-ICP-MS spot age data for zircon grains from the sample A1923 Piilikangas. Many of the analysed grains have Archean cores, and yield a wide spectrum of spot ages between c. 3.0 and 2.2 Ga, indicating presence of also possible Proterozoic inherited zircon grains or growths on Archean cores. The cluster of young ages at 1778+-10 Ma is interpreted to yield the likely magmatic age of the Piilikangas (Vaala) granite.

widest spectrum of compositions, from alkali-rich quartz diorite-tonalite to granite (SiO_2 61.0–74.2 wt.%, K_2O+Na_2O 7.90–8.91 wt.%), and a tendency towards A1-type granite compositions with relatively high HREE (Yb up to 5.8 ppm), Nb (up to 52 ppm) and Zr (up to 905 ppm). Nb/La (0.07–0.40) and especially Nb/Th (0.15–5.37) values range much higher in the Salmineva granites than the Oudonjärvi and Vaala granites but nevertheless have Nb/La ratios that remain mostly below the average upper crustal value (0.4), partly reflecting the distinctly elevated LREE that characterize all these three granite suites.

Initial testing by TIMS showed that representative samples taken from Vaala and Oudonjärvi granites (two samples) had heterogeneous zircon populations. To resolve the zircon age spectra and determine crystallization ages, LA-ICP-MS was then applied. These results indicate a probable crystallization age of about 1.78 Ga for the Vaala granite sample, 1.85 Ga for the Oudonjärvi granite, and a wide spectrum of Archean and, somewhat surprisingly, possibly also early Proterozoic zircon grains in their source domains (Fig. 2). Prior to this study, the Vaala type granites had already been dated from the Kalpio Complex to the north of the Oulunjärvi Lake, with results close to 1.80 Ga (Vaasjoki et al. 2001 and unpublished data of GTK, Fig. 1). The dated Salmineva sample is of distinctly A-type affinity and accordingly has a simple homogenous zircon grain population yielding a precise TIMS age of 1789±2 Ma, which accords with the LA-ICP-MS results of 1791±6 Ma on a nearly homogenous zircon grain population. Sm-Nd epsilon (T) values obtained for the Vaala, Oudonjärvi and Salmineva zircon-dated samples are -9.1 (1.80 Ga), -5.9 & -6.2 (1.85 Ga) and -4.9 (1789 Ma), respectively.

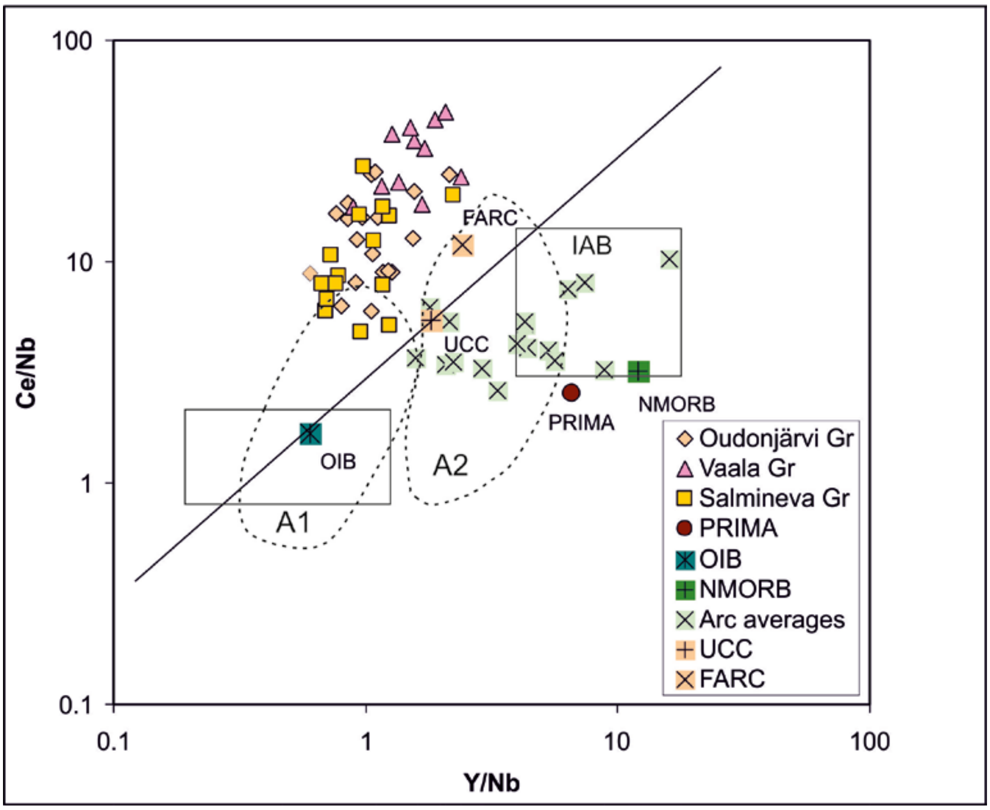

Fig. 3. Ce/Nb versus Y/Nb diagram for samples from Oudonjärvi, Vaala and Salmineva granites. Note the trend towards OIB/A1 type values, which we interpret in terms of an alkaline mafic-intermediate component in the crustal source of these granites (added to the crust before the c. 1.85 Ga emplacement of the Oudonjärvi granites). The diagonal reference line represents Ce/Y= 3.0 for average upper continental crust. Fields for IAB=island arc basalts, OIB=ocean island basalts and A1 and A2-type granites are after Eby (1990). PRIMA= primitive mantle, NMORB=average N-type mid-ocean ridge basalt, UCC=average upper continental crust, FARC=average Finnish Archaean crust.

The zircon age and Sm-Nd isotope and trace element geochemical data all indicate a dominantly crustal, mixed Archean-Proterozoic source and anatectic origin for the the Oudonjärvi and Vaala granites. The very strongly negative Nb anomalies in mantle-normalized diagrams of these rocks strongly suggest a residual mineral control for Nb in their sources. The Salmineva granite shares many features in common with the Vaala granite, the main differences being the lack of negative HFSE anomalies and tendency to (more mafic) A1 type compositions (Fig. 3). These may be consequences of higher melting temperatures and hence the lack of the inferred Nb retention, while allowing complete assimilation of all potentially inherited zircons, and resulting in an increased contribution from mafic component(s) in the source domain. Trace element ratios suggest that the inferred mafic component may have been predominantly of alkaline basaltic composition (Fig. 3). Further work on the non-A type samples of the Salmijärvi suite in particular would be needed to prove or disprove this hypothesis.

It is worth noting that at several locations in the studied area, the Oudonjärvi, and also Vaala granites, are intruded by pegmatitic granite dykes similar to those making up much of the so-called Kajaani granite, which would therefore most probably be younger than 1.80 Ga. One more important result of the present work is that prominent faults in the studied area, including the Auho and Pyhäntä faults (Fig. 1), were demonstrably active at or after 1.80 Ga, given that these faults crosscut and displace the Oudonjärvi and Vaala granites. Similarly, a young age is indicated also for the narrow Raappana fault zone (<1 km) which, in the Kivesvaara area in Paltamo, juxtaposes the Kalpio gneisses against the schists of the Kainuu Schist Belt. The young timing of Raappana faulting is also evident from the fact that foliated, mylonitic Kajaani granite is abundant within the middle amphibolite facies Kalpio Complex, immediately west of the fault zone, whereas there are no known occurrences of this granite in the upper greenschist grade Kainuu belt to the east of the fault. Finally we note a possible magmatectonic correlation between the granites in this study and similar 1.86–1.78 Ga granites in the Central Lapland Granitoid Complex, and close temporal and compositional similarity of the Vaala granites to the Nattanen type granites further north in Lapland.

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SHOSHONITIC AND ALKALINE 1.86–1.85 GA MAGMATISM AT THE CONTACT OF THE SVECOFENNIAN AND KARELIAN DOMAINS IN THE PYHÄNTÄ AREA, CENTRAL FINLAND

by

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Svecofennian gneissic plutonic-volcanic rocks and Archean gneissic TTG rocks occur in close proximity in the Pyhäntä area, separated by a merely 5–10 km wide zone of Paleoproterozoic gneisses with minor amphibolite, garnet amphibolite and metachert intercalations (Fig. 1). Contacts between these three gneissic units are geologically and geophysically sharp, demarcated by major faults. The Näläntöjärvi gneisses are commonly intruded by mafic to intermediate dikes of monzogabbro-monzodiorite (Kansanneva dikes), typically tens of centimetres to tens of metres thick and near the lake Iso Lamujärvi, by three small, internally complex mafic-intermediate alkaline plutons of monzogabbro, monzonite and syenite (Iso Lamujärvi plutons). The Kansanneva dikes sharply cut leucosomes and foliations in the Näläntöjärvi gneisses but are also metamorphosed and variably foliated to amphibolites. The Iso Lamujärvi plutons have been extensively invaded by younger granite and granite pegmatite dikes; these rocks too are mostly strongly foliated and have been metamorphosed to upper amphibolite facies grade. The Kansanneva dikes and Lamujärvi plutons have been studied here with respect to age (on zircon by TIMS, LA-ICP-MS), isotopic composition (Sm-Nd) and major and trace element geochemistry and relationships to major deformation events, in order to obtain insights into the origin and timing of their parent magmas, and thereby the tectonomagmatic and tectonic history of the contact zone between the Svecofennian and Karelian domains. This work has been done concurrently with an assessment of the Lamujärvi plutons for their potential as a resource of YREE, Nb, Ta and Zr. The exploration research by GTK has located zones of evolved syenites which are strongly enriched in Zr (up to 4000 ppm), Nb (up to 700 ppm), Ta (up to 80 ppm) and ΣYREE (up to 5600 ppm), which currently fall short of economic grades, however.

The zircon dating results include obvious magmatic ages of 1858±2 Ma by CA-TIMS and 1859±8 Ma by LA-ICP-MS for one sample (A2006) of representative monzodioritic Kansanneva dike from their Kansanneva type area. A syenite sample (A2009) from one of the Iso Lamujärvi plutons (Rannankukkula) has been

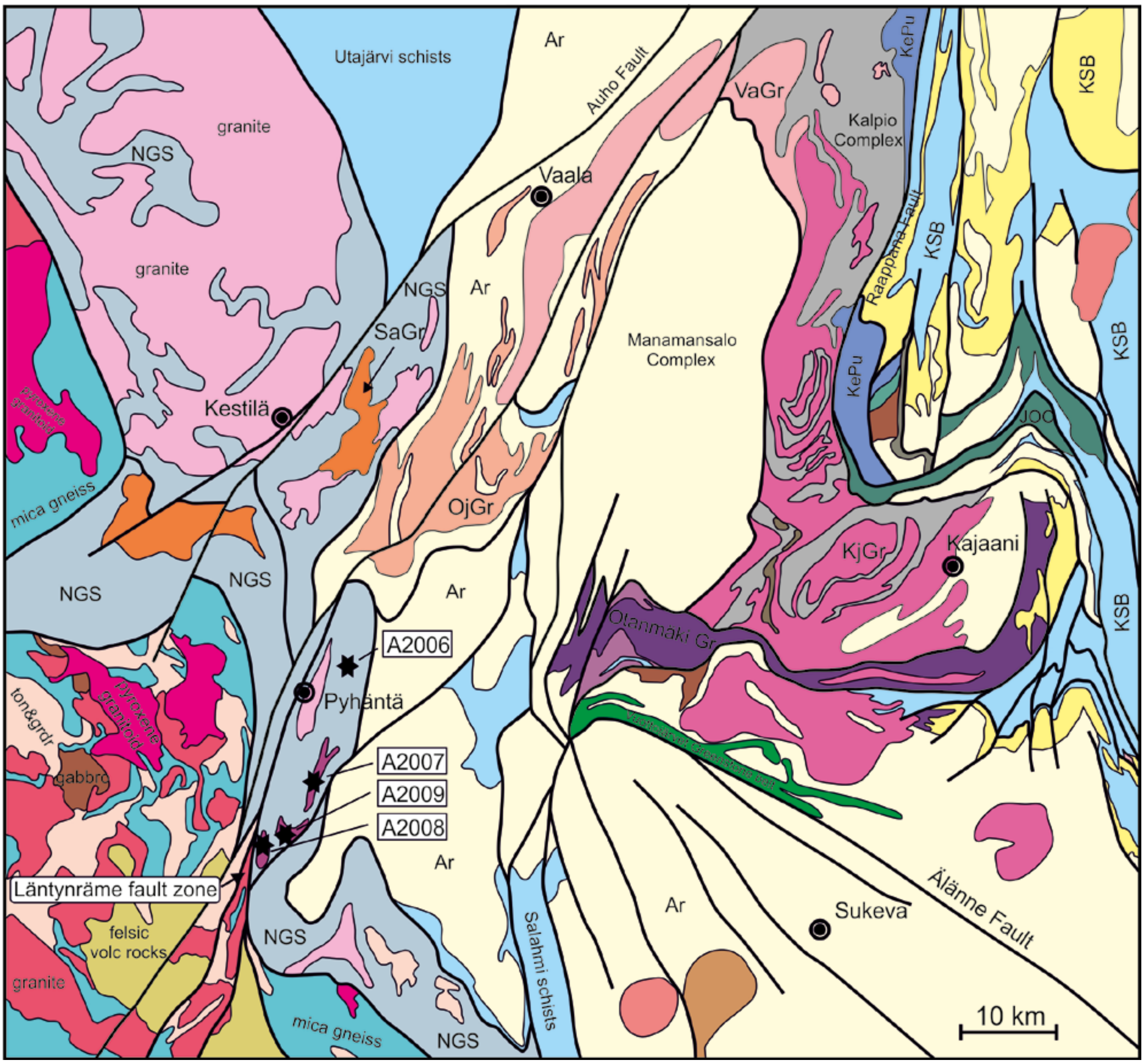

Fig. 1. Generalized geological map showing regional setting of the Lamujärvi alkaline plutons and location of samples used for zircon dating in this study: A2007/Huhmarkangas, A2008/Pienimäki and A2009/Kivimäenkangas. Monzodioritic dykes, which are plentiful in the NGS east and south of Pyhäntä have been dated by the sample A2006/Kansanneva. NGS=Näläntöjärvi Gneiss Suite, Ar=Archaean rocks, OjGr=Oudonjärvi granite (c. 1.85 Ga), SaGr=Salmineva granite (1.80 Ga), VaGr= Vaala granite (c.1.80 Ga), KePu=Keski-Puolanka Group, KSB=Kainuu Schist Belt (2.3–1.90 Ga), JOC=Jormua Ophiolite Complex (1.95 Ga), Otanmäki Gr=A1 type Otanmäki suite granites (2.05 Ga). Rocks west of the zone occupied by the NGS are Svecofennian (dominantly1.92–1.86 Ga).

dated at 1845±3 Ga by TIMS and 1851±13 Ma by LA-ICP-MS (Fig. 2). A pervasively foliated syenogranite dike (A2008) intruded into a syenite of one the Lamujärvi plutons (Pienimäki) was found to have a somewhat heterogenous but nevertheless dominantly magmatic zircon population, which was dated at 1771±9 Ma by LA-ICP-MS. $\boldsymbol{\varepsilon}_{Nd}$ (T) data obtained include −1.0 for the Kansanneva monzodiorite dike A2006 and −5.2 and −5.6 for two samples, A2007 and A2009, from the Iso Lamujärvi syenites. Respective T-DM ages are 2214 Ma, 2389 Ma and 2373 Ma.

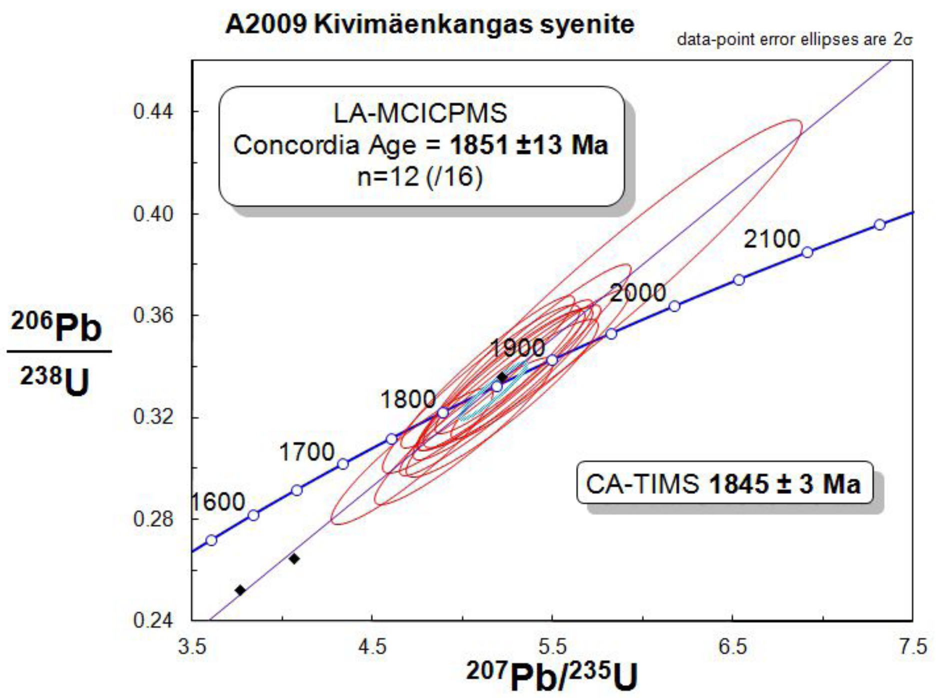

Fig 2. Concordia diagram for multigrain TIMS (black diamonds) and spot LA-ICP-MS analyses (red error ellipses) for zircons from syenite sample A2009 Kivimäenkangas.

The Kansanneva dikes in the Näläntöjärvi suite correspond to absarokite to banakite based on their major chemical composition (SiO_2 46–63 wt.%, MgO 6.2–1.4 wt.%), showing typical intraplate shoshonitic/potassic features (Müller et al. 1992) such as moderately high K_2O (1.4–4.7 wt.%), K_2O/Na_2O (>0.5 wt.%), K_2O+Na_2O (mostly >5 wt.%), Ba (mostly >1000 ppm), TiO_2 (1.0–3.3 wt.%), P_2O_5 (0.5–2.0 wt.%), ΣREE (410±211 ppm), La/Yb 33±18 and La/Nb 2.8±1.3. The evolved, fractionated nature of the suite is evident from the low Cr (<200 ppm) and Ni (<55 ppm) throughout the observed compositional range. Incompatible trace element ratios such as Th/Nb (mostly <0.20), La/Nb (mostly <2.8) and La/Yb (mostly >15) together indicate an enriched mantle source and negligible to modest crustal contamination of the derived magmas (Fig. 2). Although a post-collisional setting could be invoked for the Kansanneva dikes, this view is contradicted by major differences in their trace element characteristics compared to some classical cases of post-collisional potassic mafic-intermediate magmatism, such as the Tibetan shoshonites or Scottish appinites (Fig. 3a).

The Iso Lamujärvi plutons are an internally complex and poorly understood mixture of TiO_2 rich monzogabbros-diorites, monzonites and Zr, Nb and REE rich syenites, all with slightly nepheline bearing to quartz-free normative compositions. Both the gabbroic and monzonitic-syenitic rocks show distinct within plate OIB type magma character and have low Th/Nb (0.05–0.15) and La/Nb (0.48–1.67) ratios, thus excluding significant crustal contamination or subduction-related components. In terms of incompatible trace element ratios, the Lamujärvi rocks show more affinity with alkaline mafic-intermediate, as e.g. Kola province, than A-type granitic associations (Fig. 3b).

The high LREE/HREE and few available Sm-Nd data from the Iso Lamujärvi rocks together imply a mantle source that was enriched in LREE long before the 1.85 Ga emplacement of the Iso Lamujärvi plutons within the surrounding,

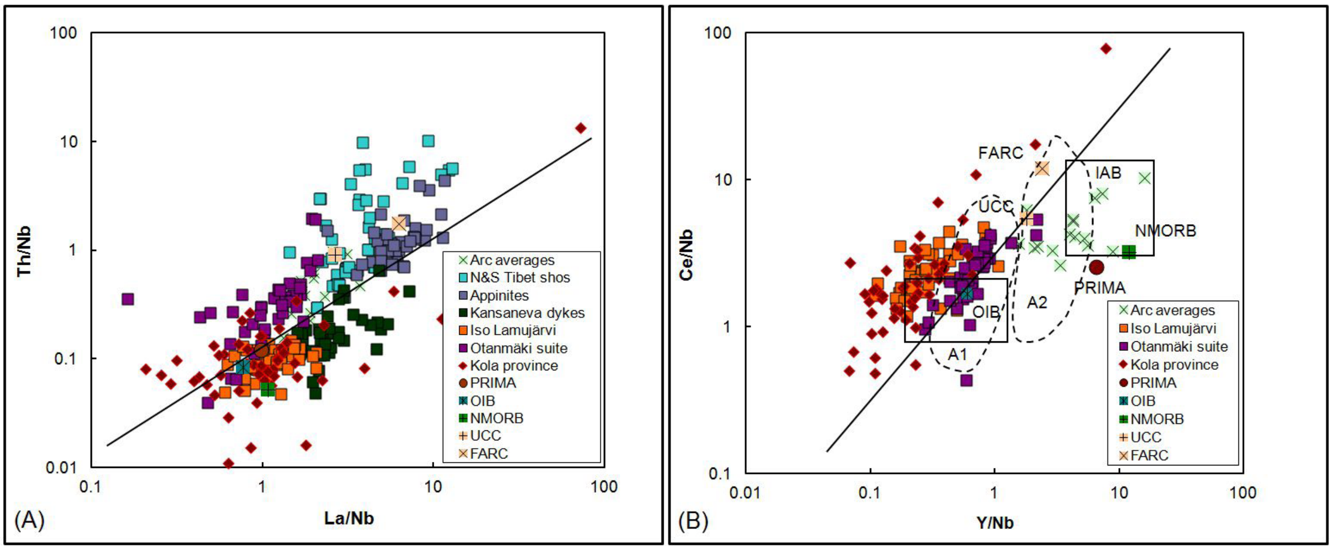

Fig. 3. (A) Th/Nb versus La/Nb diagram for samples from Kansanneva dikes and Lamujärvi alkaline plutons. For comparison, data for 2.05 Ga Otanmäki A1-type granites, Kola Province alkaline rocks (Arzamastsev et al. 2001), Tibetan post-collisional shoshonites (Williams et al. 2004) and appinites-syenites from northern Scotland (Fowler & Henney 1996, Fowler et al. 2001) are also plotted. The "arc averages" refer to estimated mean compositions of some modern magmatic arcs. PRIMA=primitive mantle, OIB=average ocean island basalt, NMORB=average N-type mid ocean ridge basalt, UCC=average upper continental crust, FARC=average Finnish Archean crust. The diagonal reference line is for Th/La= 0.12 corresponding to primitive mantle. (B) Ce/Nb versus Y/Nb diagram for samples from the Iso Lamujärvi plutons. The diagonal reference line is for Ce/Y=3.0 corresponding to average upper continental crust. Fields for IAB=island arc basalts, OIB=ocean island basalts and A1 and A2 granites after Eby (1990).

presumably >1.90 Ga, Näläntöjärvi metawackes-pelites. An ancient lithospheric mantle source is thus indicated but further speculation of its nature is complicated by the possible allochthonous nature (as discussed below) of the plutons and enclosing Näläntöjärvi gneisses. The study here is still in progress and more data on the isotope geochemical characteristics of both the Kansanneva and Iso Lamujärvi suites are required before some of the more important remaining petrologic questions can be properly addressed, e.g., the petrogenetic relationship of the two suites and more precise characterization of their mantle source(s). Below we emphasize some regional tectonic implications of the new data.

Available mapping suggests that Kansanneva type dikes are very common in the Näläntöjärvi gneisses throughout the entire Kansanneva–Lamujärvi area (as also elsewhere in the Näläntöjärvi suite), whereas they appear to be absent from the adjoining Archean gneiss blocks. Combined with field structural observations indicating a gently west-dipping attitude for the Näläntöjärvi-Archean contact, this distinct difference suggests that the contact is defined by a post-1.85 Ga west-dipping thrust fault, which was later deformed by the major sinistral S-fold seen in the area SE of the Iso Lamujärvi Lake. In the light of this inference, the Näläntöjärvi suite could be an allochthonous unit thrust together with the Kansanneva dikes and Iso Lamujärvi plutons from a "westerly" source into its present location (from how far away remains an open question). The pervasive deformation of the late, presumably <1.80 Ga granites and pegmatites in the Iso Lamujärvi area suggests that faulting and deformation in this area persisted in time until at least 1.80 Ga. This applies also to the narrow Läntynräme fault zone that separates the Näläntöjärvi suite rocks from the dominantly plutonic-volcanic rocks of the Svecofennian area in the west. How much history the faults in the Läntynräme zone had before and after 1.80 Ga is still unclear. The ongoing work includes also dating of the protomylonitic granodioritic-granitic rocks (some parts possibly <1.80 Ga) directly within the Lantynräme fault zone. The results of this dating have the potential to be especially useful in understanding the timing and nature of tectonic processes in the Svecofennia-Karelia contact zone, both in the present study area and more generally.

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Ni AND Co IN TALVIVAARA PYRRHOTITE

by

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Ni and Co contents of pyrrhotite from 21 samples representing all the more common variants of the Talvivaara black shale hosted sulfidic (c. 9 wt.% S on average) Ni-Zn-Co-Co deposit (1550 Mt @ 0.22% Ni) have been microanalyzed (N=179) for this study. This extensive survey indicates that pyrrhotite throughout the Talvivaara deposit had a remarkably uniform composition with 4891±688 ppm Ni and systematically less than 100 ppm Co. These are within the range of values commonly reported (e.g. Misra & Fleet 1973 and cited references) for pyrrhotite in magmatic nickel ores, i.e. pyrrhotite that has been unmixed by subsolidus cooling from a monosulfide solid solution (mss). As with the pyrrhotites of magmatic Ni ores, Talvivaara ore pyrrhotites also commonly contain exsolution flames and grains of relatively Co-poor (typically <2 wt% Co) pentlandite. The presence of staurolite, garnet and cordierite in pelitic rocks and the talc-olivine assemblage (serpentinized) in ultramafic rocks indicate that amphibolite facies (at least 550 °C) temperatures were attained in the Talvivaara area during the thermal peaking of the regional (Svecofennian) metamorphism. We interpret on the basis of these findings that a metamorphic nickel-rich mss phase universally developed in the iron sulphide and Ni-rich (1000-5000 ppm) black shales during metamorphic peak conditions, and that the present pyrrhotite and pentlandite have been unmixed by subsequent cooling from this mss. A complete equilibration of the mss with host silicates and sulphides was obviously attained during peak metamorphism; as a result often >90% of the whole rock nickel and also iron in Talvivaara ore is now located in the metamorphic pyrrhotite and its pentlandite exolutions. The results of this study have profound implications for interpretation of e.g. sulfur, nickel and iron isotope data from the Talvivaara pyrrhotites.

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GEOLOGIC CORRELATION AND SIGNIFICANCE OF THE PROMINENT SAARIVAARA REFLECTOR FROM THE HIRE V7 VIBROSEISMIC SURVEY IN THE OUTOKUMPU AREA

by

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One of the most prominent seismic (acoustic) reflectors so far identified in Finland is located below the vibroseismic survey line HIRE Polvijärvi V7. This prominent feature is imaged at depth along most of the profile, over a distance of nearly 11 km. The Profile V7 migrated image shows that the upper surface of the approximately kilometre-thick reflector package lies at a depth of about 500 m beneath Saarivaara, at the NE end of Profile V7, where it is seen to dip eastwards, to a depth of 2.5 km beneath Perttilahti, near the eastern end of the profile, where it is somewhat less distinct but still clearly discernible (Fig. 1). In order to study the geologic correlation and significance of this reflective package, which we refer to as the Saarivaara reflector, we have drilled two 150 m deep diamond drill holes at Ittikkapöksynkangas, about 1.5 km NW of the Saarivaara end of Profile V7, where the reflective package should intersect the surface, based on up-dip extrapolation from the V7 seismic image (cf. Figs. 1 and 2). The Itikkapöksynkangas area is poorly exposed; in the drilled area there is only one known outcrop of calc-silicate gneiss. Previously published geological maps indicated that the two holes at Itikkapöksynkangas would be expected to intersect the contact between Archean basement (granite gneiss with amphibolite intercalations) and overlying mica schists of the Outokumpu Allochthon, dipping at about 20 degrees towards the east.

Instead, the two holes revealed at least 300 m thick supracrustal sequence dipping at 30 degrees SE and composed of intercalated amphibolite, black schist, mica schist, quartzite and arkosite-mica quartzite (Fig. 3), and in which most of the amphibolite layers seem to represent dolerite dykes or sills. The total thickness and contacts of the dissected sequence remain unresolved, but based on inferences from field mapping data, the overlying mica gneisses of the Outokumpu Allochthon occur about 100 m to the east, while at a similar distance to the W, the sequence must be underlain by highly deformed, foliated granodioritic augen gneisses of the Archean basement complex. Thus the total thickness can be constrained to between 400 and 500 m. The actual thickness and nature of contacts with the Outokumpu Allochthon and Archean gneisses will be addressed by future additional drilling.

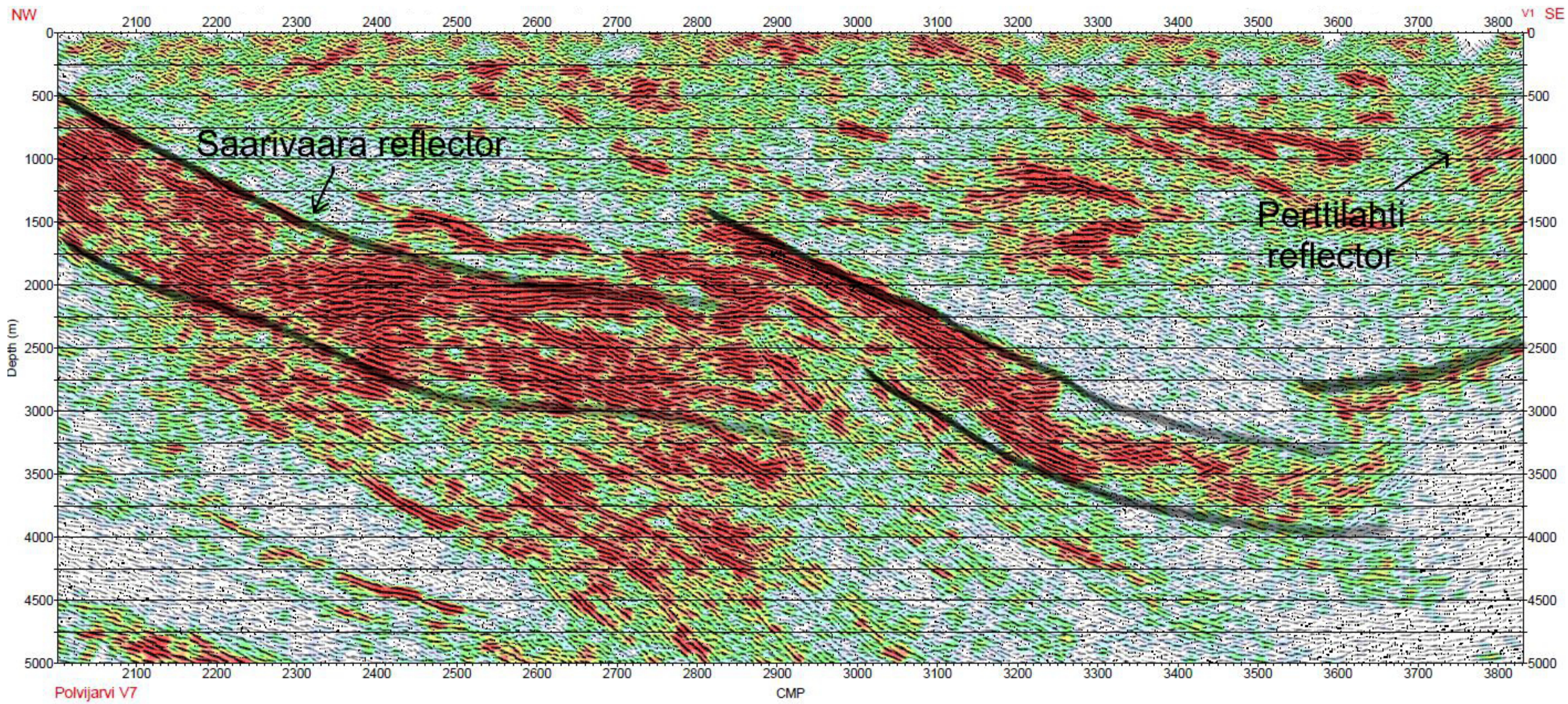

Fig. 1. Reflection seismic image from the nearly 11 km long HIRE Polvijärvi V7 survey. The NW end of the almost linear survey line is situated at Saarivaara near the W margin of the Outokumpu Allochthon (cf. Fig. 2) and the SE end at Perttilahti where it barely intersects the main Outokumpu ore belt. In the image the background gray traces represent amplitude variations on a decibel scale and red hues high values (Heinonen et al. 2011). The Saarivaara reflector is outlined by dark-grey brush strokes. Location of the Perttilahti reflector is shown by black arrow. The brightest areas in the lower part of the image/section (<2000 m) are probably related to late granite intrusions.

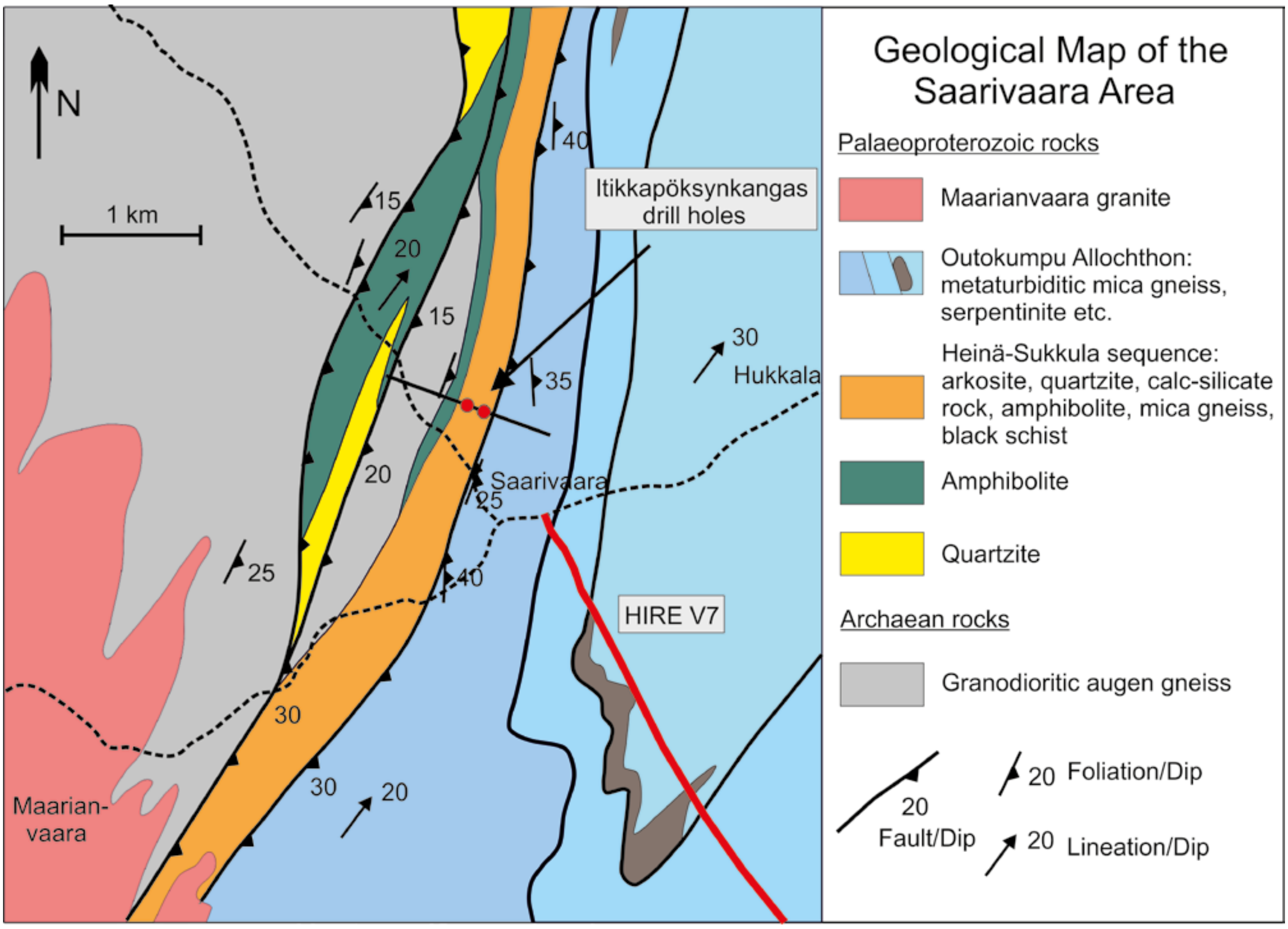

Fig. 2. Generalized geological map of the Saarivaara area and location of the Itikkapöksynkangas drilling site at the NE end of the HIRE Polvijärvi V7 survey line.

Ninety rock samples from the Itikkapöksynkangas drill cores have been measured for their susceptibility, intensity of remanent magnetization, density and P-wave velocity. The P-wave measurements were done by sonar elements at room pressure and temperature, in most cases nearly perpendicular to sample foliation. Densities were found to vary between 2452 and 3181 kg/m^3, while P-wave velocities varied between 3232 and 7168 m/s. The P-wave velocity results are somewhat ambiguous as a variable, sample-dependent increase in measured velocities was noted with the time applied to sample wetting. The velocities above were measured after 59 days immersion and should approach "terminal" values. Seismic impedance values calculated for the samples range from 0.835x10^7 to 2.250x10^7 kg/m^{2}s. Although uncertainty remains, for various reasons, concerning how to compare the measured density and velocity data with down-hole gamma-gamma and sonic log data or "real" values in rock at various depths, we note that both laboratory (for samples both at atmospheric pressure and pressurized) and drill hole measurements have previously yielded broadly similar information for important relative density and impedance variations (as in the R2500 case mentioned below).

It has been also proposed that the Saarivaara reflector could be attributed to an unprecedentedly thick and extensive Outokumpu "sequence" below Profile V7. Based on the evidence presented above, we are confident about that this reflector is, however, probably over its entire extend, caused by the same sequence that we have drilled at the Itikkapöksynkagas site, which presumably represents

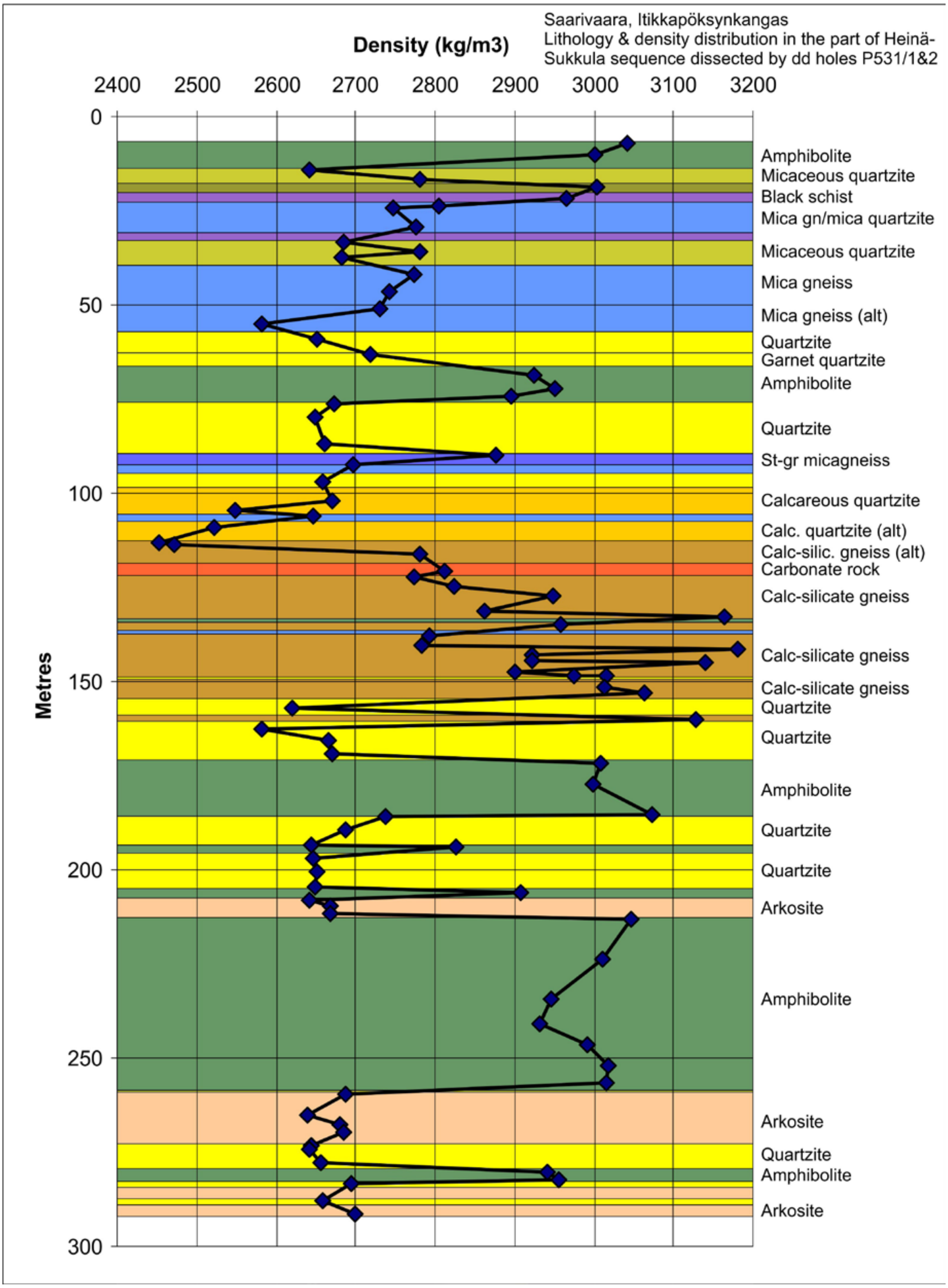

Fig. 3. Lithologic column constructed for the strata intersected by the drill holes at Itikkapöksynkangas. Density distribution in the rock column, based on 90 samples, is shown by the blue line with diamonds.

the widespread originally platformal "marine Jatuli" (2.10–2.05 Ga?) quartzite-dolomite-mafic volcanic and intrusive association. This is conceivable as the observed variations in rock densities, P-wave velocities and derived acoustic impedances are of the same magnitudes as those of the serpentinite-calc-silicate rock-black schist related reflector unit intersected by the R2500 deep hole NE of the town of Outokumpu town (Airo et al. 2011, Heinonen et al. 2011, Kern & Mengel 2011). Further, individual density units in the gently dipping Itikkapöksynkangas section are on the order of several metres to tens of metres thick and are often very sharply bounded and internally strongly foliated internally, all of which are factors that should enhance acoustic reflectivity. It is also worth noting that the supracrustal sequence at Itikkapöksynkangas (400 m) is substantially thicker than the serpentinite-related reflector unit (150 m) in the R2500, and that there are relatively high density amphibolite layers (after dolerite sills) in the strongly foliated relatively low density granodiorite gneisses below the supracrustal sequence at Itikkapöksynkangas, which may explain why the Saarivaara reflectivity package is up to 1300 m in total thickness. Below Profile V7, the thickness of the reflector package may be more or less than this figure, due to "original" thickness variation and the effects of tectonic imbrications, for example related to west-directed late thrusting, which is apparent in the V7 seismic images. We consider that the brightest areas in the seismic image in Fig. 2 probably represent late granite intrusions.

Finally, we deduce that other laterally extensive prominent reflective packages observed by the seismic surveys of the Outokumpu area can be attributed to supracrustal or basement gneiss units with laterally persistent layered variation in rock type/density, as in the originally platformal quartzite-dolomite-mafic sill/volcanic rock Saarivaara package – rather than Outokumpu formations, which tend to form relatively thin pipe-like or lenticular bodies with considerable internal 3D complexity, and which therefore are prone to cause only dimensionally limited and diffuse-spotty seismic reflectivity. A typical example of the latter case is given by the diffuse-spotty seismic reflectivity related to the sizeable Perttilahti "Oku-formations" at the very SE end of Profile V7, 300–1000 m below the surface (Fig.1).

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LITHOSTRATIGRAPHY, SEDIMENTARY ENVIRONMENT AND ORIGIN OF THE TALVIVAARA BLACK SCHIST HOSTED Ni-Zn-Cu-Co DEPOSIT

by

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MAIN LITHOSTRATIGRAPHIC UNITS IN THE TALVIVAARA AREA

The giant (1.55 billion ton) but low-grade (0.22 wt.% Ni, 80% of metal value) black schist hosted Talvivaara Ni-Zn-Cu-Co deposit outcrops in two subareas: Kolmisoppi and Kuusilampi. The nearly 10 km long deposit is situated within an extensively faulted and folded amphibolite grade environment making it difficult to reconstruct original stratigraphical and sedimentological units and their relationships.

The present understanding of the Talvivaara area from field mapping and drill core data indicates that the lithostratigraphic framework hosting the deposit comprised the following distinct units (listed in the assumed younging order). (1) Archean gneissic-migmatitic basement. (2) Jatuli stage (c. 2.3-2.1 Ga) shallow water (platformal) quartzites with two main units recognized: the Sorkolehto Fm (at least 250 m) comprising cross to parallel bedded feldspathic quartzites, and the Vuohimäki Fm (at least 250 m) characterized by ultramature, fine-grained and dominantly parallel bedded orthoquartzites. (3) Lower Kaleva stage (c. 2.1-1.95 Ga) medium to very thinly bedded micaceous metawackes and pelites with intercalations of massive-graded quartz rich sands and mass-flow conglomerates and minor metacarbonate rocks ("tremolite skarns") in the Hakonen Fm (at least 400 m). These rocks were apparently deposited in an amagmatic rift basin developed within the cratonic platform recorded by the Jatuli stage quartzites. (4) Lower Kaleva stage metal rich black metashales in the Talvivaara Fm (at least 50 m), with metacarbonate rock intercalations especially in the basal parts of the formation and increasingly more laminated pyrite mud intercalations towards the top, where Mn-rich black shale intercalations are also present. The highly base metal-enriched lower part of the Talvivaara Fm corresponds to the Talvivaara ore. (5) Upper Kaleva stage (1.95-1.90 Ga) medium to thin bedded massive black-grey feldspathic metawackes with abundant variably pyritic black shale intercalations, constituting the Kuikkalampi Fm (at least 250 m). (6) Grey feldspathic wackes and pelites with rare graphitic mud intercalations present in the Viteikko klippe (preserved max thickness c. 200 m). The base of the Viteikko klippe is marked by thin lenses of mantle peridotite altered to talc-carbonate rock and talc schist. This unit is correlated with the Jormua-Outokumpu Allochthon. Accordingly, the Viteikko wackes and pelites are considered younger than 1.92 Ga (Lahtinen et al. 2010).

The Talvivaara formation in the Kuusilampi area is folded to an antiformal structure cored by mica schist (partly graphitic-sulfidic) intercalated with quartz sands of the Hakonen Fm. Drill core observations suggest a rather abrupt but gradational change from this "footwall quartzite" to the Talvivaara Fm, which for its basal part comprises mainly massive thickly bedded to laminar, variably sulfidic and graphitic muds with typically 2–7 vol.% metacarbonate ("black tremolite±diopside skarn") intercalations, which also typically contain high sulfide and graphite contents. The apparent footwall of the Talvivaara Fm is also in contact with Hakonen Fm rocks in the Kolmisoppi area, although the structural complexity of this area is poorly understood.

The Kuikkalampi Fm black sands and muds structurally overlie the Talvivaara Fm both at Kuusilampi and Kolmisoppi but the exact nature of the Talvivaara to Kuikkalampi transition is still inconclusively defined. Though an abrupt-gradational transition appears most likely, the possibility of a folded cryptic thrust contact between the two units cannot yet be excluded. The fact that the Kuikkalampi Fm sands are immature feldspathic greywackes in contrast to the quartz-mica wackes in the underlying Talvivaara and Hakonen formations implies a major difference in terms of source compositions or at least sediment maturities. In this respect Kuikkalampi sands show more similarity to sands in the Viteikko klippe. Further support for this correlation comes from that both Kuikkalampi and Viteikko samples yield slightly higher ε_{Nd} (1950 Ma) values (between -1.3 and -2.0) than Talvivaara and Hakonen Fm samples (between -2.9 and -6.7). Kuikkalampi black muds differ from the Talvivaara black schists also in having significantly higher Mo but lower Ni. Temporal and provenance correlation of both Kuikkalampi and Viteikko sands with those in the Outokumpu Allochthon is here assumed (will be checked by dating of zircon grains).

SEDIMENTARY ENVIRONMENT OF THE TALVIVAARA FORMATION

Large portions of the Talvivaara Fm are strongly structurally reworked and disrupted but locally, within less deformed domains, primary sedimentary features may be well preserved. Observations from such domains indicate that the most voluminous component of the Talvivaara Fm comprised texturally and compositionally often very uniform, homogenous fine-grained beds (or amalgamated sets of beds) of massive muds, sometimes exceeding 1 m in thickness. Weakly sulfidic-graphitic layers of quartz-rich sands similar to the quartz sands of the Hakonen Fm, are a minor but rather frequent component especially in the lower part of the Talvivaara Fm. These distinctive layers commonly have sharp erosional bases, show clear grading, mud chips and load and water escape structures in their basal parts, attesting to a subaqueous mass flow ("turbidite") origin. The extreme compositional homogeneity and massive to faintly graded appearance of also many thicker mineralized mud layers suggests that they too were deposited from mass flows. A similar origin is likely also for the greater part of the intercalated thinner bedded to laminated muds. Deposits by sediment fallout from the overlying water column are represented by intervals of laminated highly pyritic muds and Mn-enriched muds. It is notable that these layers, which are distinctly more common in the upper part of the formation, are usually lower in metals than the dominating massive muds. The banded pyritic muds commonly contain thin dark black interbeds and laminae with high C and P contents. These layers also likely represent in situ deposition, perhaps during mass mortality events affecting bacteria in the water column.

The black calc-silicate rocks represent a genetic puzzle because of their usually pervasive recrystallization to mostly very coarse tremolite±diopside assemblages. Derivation from carbonate-rich precursors is obvious, however, and locally considerable amounts of carbonate may still be present, interstitial to the coarse tremolite±diopside. An origin as clastic turbidite sands-muds dominated by carbonate+-quartz seems most likely, based on the often sharp contacts and solitary occurrence of the individual layers. A distinct seawater-type fingerprint in the REE patterns of the metacarbonates suggests that a significant scavenced or microbially induced component was present in their REE budgets; the source of the calcareous material therefore most likely was in shallow water stromatolites or deeper water microbialitic carbonate sequences.

Mass flow deposition characterizes the entire Talvivaara Formation. There are no observations in any of the included sediment types for distinct cross-bedding (dunes), ripples, traction laminae or mudcracks. Hence deposition in a relatively deep basin or at least below the storm wave base (250 m) is likely. We infer deposition in the rift basin that developed during the preceding Hakonen Fm sedimentation. Although most of the deposited material was fine-grained clay-rich mud, there were frequent pulses of coarser sand apparently from the same platformal carbonate-intercalated quartzitic sources that characterized the deposition of the Hakonen Formation. As we infer below, this rift basin must have had unrestricted access to the world's major ocean. Importantly, there is no evidence presently for volcanism or other type of magmatic activity during the deposition of any of the Hakonen, Talvivaara or Kuikkalampi sediments.

ORIGIN OF THE TALVIVAARA DEPOSIT

A characteristic feature of the Talvivaara Fm is the often extreme compositional homogeneity within thicker individual mud beds, combined with variations between different beds, for both major and trace element contents and ratios, including base metals. This suggests that metals were introduced in the mass flows and thus the mineralization was mainly of redeposited origin. Notable differences in metal ratios and contents preserved between individual intercalated beds and frequent occurrence of non-mineralized sandy-silty layers between highly mineralized mud layers preclude the possibility of major diagenetic or syntectonic-metamorphic redistribution of metals. Laminated pyrite-rich muds, Mn-rich muds, very graphitic and graphitic-phosphatic muds, which are more common in the upper part of the formation, most likely represent in situ deposition from the overlying water column. Metal concentrations in these layers are on average lower than in the mineralized massive muds. This applies especially to the laminated pyrite muds. Overall, in situ syngenetic deposition seems to have made only a minor contribution to the metal budget.

Because of the resedimented-recycled nature of the Talvivaara mineralization, establishing the primary origin and environment of the metal enrichment is a difficult task. One could argue for an especially Ni-enriched ultramafic and/or mafic sediment source as a part of the explanation. However, trace element ratios such as Ti/Al, Sc/Al or Cr/Al reveal that in this respect there was no significant difference compared to the lowly to non-mineralized muds in the underlying Hakonen Fm. In particular, there is no diagnostic chemical or petrographic evidence of any enhanced clastic ultramafic contribution. A near-field hydrothermal source for the strongly enriched Ni, Cu, Zn and Pb, from seafloor hot springs, has been proposed previously (e.g. Loukola-Ruskeeniemi & Heino 1996), but there are no signatures of hydrothermal processes in the geochemistry of the Talvivaara Fm nor in the underlying Hakonen Fm. For example, a REE survey shows remarkably uniform shale type normalized patterns for all dominant rock types in the Talvivaara Fm, resembling those from the muds in the underlying Hakopuro Fm. However, there is a perceptible though slight enrichment in HREE, which is suggestive of minor seawater-derived, rather than hydrothermal, component in the REE budgets. Moreover, chondrite-normalized REE patterns lack the positive Eu anomalies typical of hydrothermally influenced sediments; some slight anomalies have been observed in shale-normalized patterns but are clearly provenance (dominantly Archean) related.

High contents of primarily organic matter (now degraded to graphite) and enrichment in redox-sensitive metals such as Mo, V, Se, U and Cd in the Talvivaara mineralized muds, to concentrations that are typical for many black shales, suggest that a large resedimented black shale component was present in the massive mineralized muds. However, as base metal/redox sensitive element ratios are much higher in Talvivaara ore than in black shales in general, simple recycling is not a sufficient explanation for the base metal mineralization. Perhaps the most revealing hint presently available for the origin of the base metal enrichment is that base metals ratios (e.g. Zn/Ni and Cu/Ni) in the mineralized turbidite muds are, despite the high enrichment, similar to ratios in local less base metal-enriched sulphidic-graphitic shales, as well as in other less base metal-enriched black shales. This suggests that the primary control may still have been by normal black shale enrichment mechanisms but in an environment where the basinal waters were temporally abnormally strongly enriched in the base metals. The reason and primary environment of such metal enrichment remains obscure but it can be assumed that the metal source must have been in the global ocean system, simply to facilitate the huge magnitude of nickel stored in both the Talvivaara deposit and the associated less metal-enriched black shales (especially if all black shale/schist in the Kainuu–North Karelia area is considered).

Apart from the syngenetic-resedimented origin for its metal enrichment, the Talvivaara deposit owes much to later regional deformation and metamorphism, which greatly increased average sulphide grain size and transformed nearly all Ni into peak metamorphic monosulfide solid solution from which the relatively easily soluble pyrrhotite and pentlandite, presently hosting, on average, >80% of whole rock Ni, have been retrogressively unmixed. Metamorphic decarbonation reactions also eliminated most of the acid neutralizing carbonate from the mineralized muds and intercalated carbonate rocks. Moreover, compressional folding and fault duplexing locally greatly increased the mineable ore volumes. Without these secondary processes it is doubtful that the Talvivaara deposit would have been economically viable.

Finally, Talvivaara rocks provide not only a significant new source of metals for the perpetually (?) increasing demand by humans for construction and manufacturing, but also offer valuable insights into the composition and conditions of Earth's atmosphere and hydrosphere as they were at about 2.0 Ga. For example, the observed moderate enrichment in Mo (c. 60 ppm on average) and huge amounts of pyrite and pyrrhotite in the Talvivaara Fm suggest that a significant amount of oxygen must have been present in the atmosphere, facilitating the indicated extensive oxidative weathering of Earth's continental rock masses. A shift to even more oxidative conditions seems to be recorded by black shales in the presumably somewhat younger (<1.92 Ga ?) Kuikkalampi Fm based on their significantly higher Mo contents (often >100 ppm).

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PALAEOPROTEROZOIC 1.93–1.92 GA SVECOFENNIAN ROCK UNITS IN THE NORTHWESTERN PART OF THE RAAHE–LADOGA ZONE, CENTRAL FINLAND

by

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The Palaeoproterozoic bedrock of the northwestern part of the highly tectonized and metamorphosed NW-trending Raahe–Ladoga Zone (RLZ) belongs to the Svecofennian (1.95−1.80 Ga) domain and is located between the Archaean basement complexes (3.1–2.6 Ga) in the east and the Svecofennian Central Finland Granitoid Complex (1.89−1.87 Ga) in the southwest. The Vihanti−Pyhäsalmi district (Fig. 1) in the NW part of the RLZ has been one of the most significant base metal mining areas in Finland since the 1950's (Kousa & Luukas 2004).

The metavolcanic rocks of the Vihanti−Pyhäsalmi district are divided into the Pyhäsalmi and Vihanti groups as presented in the Digital map data base (Bedrock of Finland − DigiKP) and in the database for stratigraphic geological units (FINSTRATI). These two groups represent the oldest volcanic event recorded in the RLZ and thus form part of the older Svecofennian phase of development. The relationship between these two groups and the paragneisses of the Näläntöjärvi suite in the east is unambiguous. The third rock unit which is included within the older Svecofennian in the RLZ is the Venetpalo plutonic suite which is characterized by gneissic tonalitic intrusions. Gneissic tonalites of the Venetpalo suite are interpreted as subvolcanic intrusive rocks closely associated with to the oldest felsic volcanic event. Structurally all these units are generally situated within regional antiformal structures.

The Pyhäsalmi group is a bimodal volcanic association characterized by felsic and mafic units. Quartz porphyries and volcanic breccias and their altered varieties (Fig. 2) are the more common felsic rock types. Mafic volcanic rocks locally show well-preserved primary features including pillow lavas, with amygdales filled by plagioclase, carbonate or epidote, pillow breccias and also pyroclastic beds (Figs. 3 and 4). The Pyhäsalmi volcanics are dominantly low- to medium-K rhyolites, transitional between calc-alkaline and tholeiitic affinity, and sub-alkaline low- to medium-K tholeiitic basalts and basaltic andesites.

Voluminous intermediate to felsic volcanic rocks with calc-silicate rock intercalations (U−P-horizon) and metagreywackes are typical of the Vihanti group. The Lampinsaari and Vilminko formations are divided into several lithological

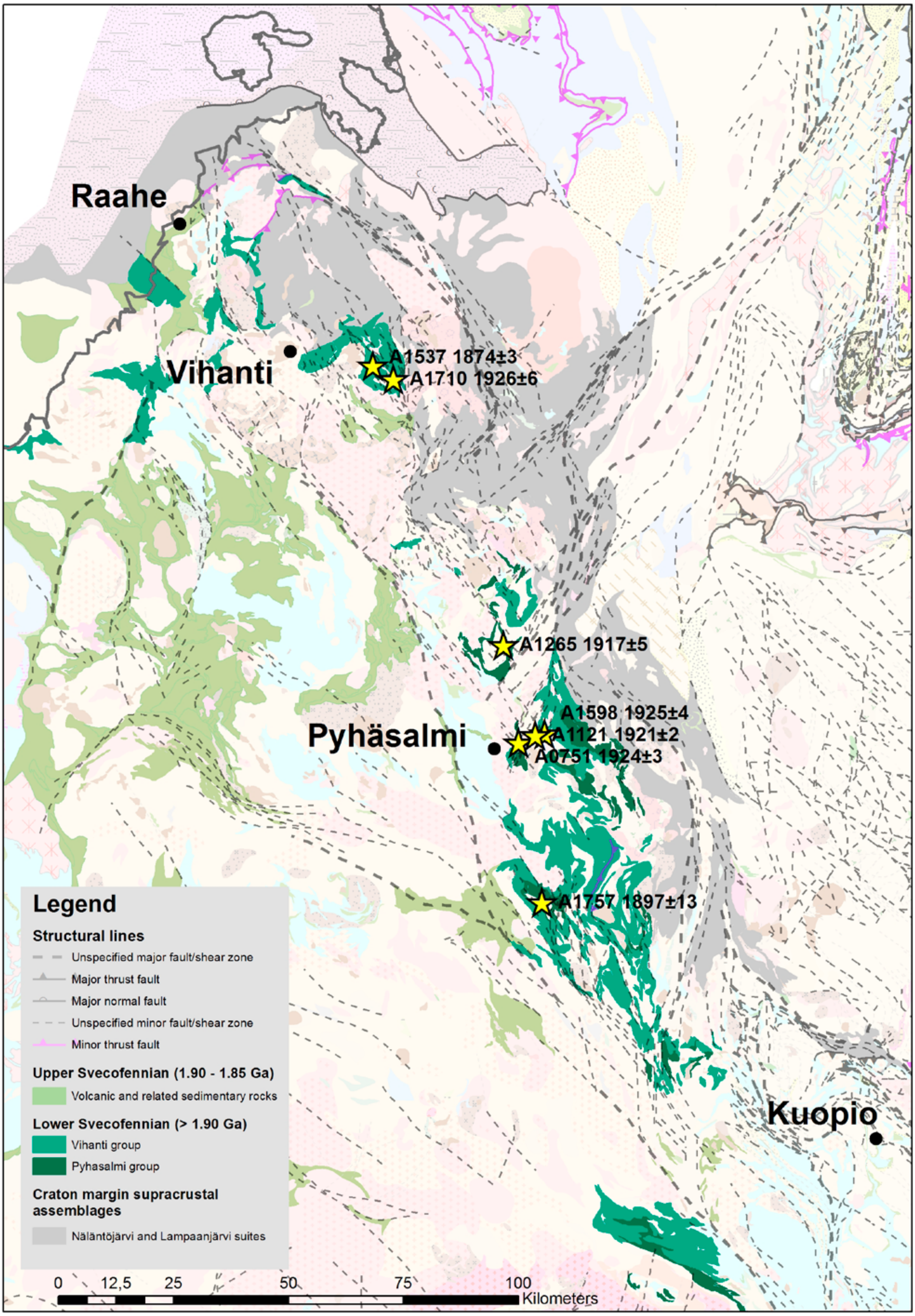

Fig. 1. Distribution of thee Vihanti and Pyhäsalmi groups and locations of samples selected for dating. Map generalized from the Bedrock of Finland – DigiKP base (referred 30.03.2012).

members where intermediate mainly andesitic to dacitic volcanic tuffs and tuffites are most abundant (Fig. 5). Primary volcanic structures are not well preserved due to locally intense deformation and the rather high, amphibolite facies metamorphic grade. However, volcanic breccia texturess have been observed in exploration drill holes. Porphyritic textures with plagioclase and/or quartz are abundant in felsic and intermediate rocks. Subordinate dacitic to rhyolitic

Fig. 2. Altered felsic metavolcanic rock (garnet-cordierite-sillimanite) intruded by tonalitic dyke in the Kangasjärvi area, 30 km south of Pyhäsalmi.
KKJ-3 coord. X=7031763, Y=3454648. Photo: Jukka Kousa, GTK.

Fig. 3. Low-K basaltic pillow metalava from theTetrinmäki formation, Pyhäsalmi group.
KKJ-3 coord. X=7069185, Y=3458940. Photo: Jukka Kousa, GTK.

Fig. 4. Mafic pyroclastic breccia at Koivujärvi, about 25 km south of Pyhäsalmi. KKJ-3 coord. X=7037700, Y=3463320. Photo: Jukka Kousa, GTK.

Fig. 5. Plagioclase porphyritic massive rhyodacitic rock intruded by mafic dike. Both rock types have been folded and sheared and quartz veins fill late pressure minima. Lampinsaari, Kiviharju. KKJ-3 coord: X=7146320, Y=3408900. Photo: Jukka Kousa, GTK.

volcanic, calc silicate rocks, graphite-bearing tuffaceous schists (black schist) and minor mafic subalkaline basaltic volcanics occur as intercalations in the intermediate rocks. The uppermost member is composed of psammitic rocks, probably of recycled volcanic material.

Lithostratigraphical relationships between rock units in the Vihanti–Pyhäsalmi district are still rather tentative, since poor outcrop density precludes direct observation of contact relations. Therefore, isotopic dating of volcanic and related intrusive rocks has been very important. Several attempts have been made to obtain relevant age constraints for the above-mentioned volcanic rocks of different stratigraphic units and most of these results have been described in earlier reports and publications. Zircons in the felsic volcanic rock samples from the massive sulphide deposits in Pyhäsalmi and Lampinsaari (Vihanti) were too fine-grained for dating. Here we present the latest updated (CA – chemical abrasion) or previously unpublished results of some important rock types in the study area (Fig. 1). The earlier TIMS samples (Vihanti group: A1710-Kokkoneva, Pyhäsalmi group: A0751-Kettuperä, and Venetpalo suite: A1265-Sarakangas) have been analysed by the CA-TIMS technique. All samples have been analysed at the isotope geological laboratory of the GTK.

The Kettuperä gneiss (A0751) in the Pyhäsalmi group is interpreted as the oldest felsic volcanic member of the Ruotanen formation. Previous zircon U-Pb dating result was 1932±12 Ma and the new CA-TIMS result gives an age of 1924±3 Ma, which is considered to be a reliable constraint on the age of volcanism. Published (TIMS) age of 1921±2 Ma from the Riitavuori rhyolite (A1121) and an unpublished age of 1925±4 Ma from the rhyolite sample A1598 (drill hole PyO/Mu-116) at the mine area are both from the stratigraphically younger Mullikkoräme formation and these results indicate that the rocks in the Pyhäsalmi group were formed in a rather short period within few million years.

The Vihanti group is represented by the Kokkoneva quartz porphyry sill (sample A1710) for which the earlier TIMS result was 1922±6 Ma, compared to the revised CA-TIMS age of 1926±3 Ma. These ages are within error limits the same as those obtained from the Pyhäsalmi group volcanic rocks.

The Venetpalo plutonic suite along the RLZ is composed of numerous more or less gneissic granitoid intrusions which are typically of tonalitic composition. The above- mentioned Kettuperä gneiss was previously considered to be the type locality but now the Venetpalo intrusion near Kärsämäki has been chosen as the type location for this suite. The earlier unpublished TIMS age of the Sarakangas sample (A1265) was 1917±13 Ma. The CA-TIMS analysis gives data slightly above concordia with a Pb/Pb age of 1920±3 Ma. Nevertheless, all seven data points plot on a single chord and yield an upper intercept age of 1917±5 Ma with only slight scatter. The other example of this plutonic suite is Mustinvuori (A1757) from the Kangasjärvi area 30 km south of Pyhäsalmi, which gives a rather discordant TIMS age of 1897±13 Ma (unpublished).

The Pyhäsalmi and Vihanti groups represent the lowermost Svecofennian stratigraphical units (older than 1.90 Ga) in the RLZ. We consider on lithological grounds that the Vihanti group is slightly younger than the Pyhäsalmi group. The rocks of the Vihanti group are abundant in the Vihanti area and in the Pielavesi area but subordinate in the Pyhäsalmi–Kiuruvesi area. The new age results are same within errors for both groups and thus the separation of these supracrustal rocks into two groups is based more on lithological differences than the ages. Both groups are intruded by voluminous Svecofennian intrusive rocks (1.89–1.87 Ga).

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REFLECTION SEISMIC SURVEYS IN PREVIOUSLY MINED AND EXTENSIVELY EXPLORED AREAS: IMPLICATIONS FOR MINERAL POTENTIAL

by

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The goals of the HIRE (High Resolution Reflection Seismics for Ore Exploration 2007–2010) project have been to (1) extend seismic reflection surveys to exploration of the Precambrian crystalline bedrock of Finland, (2) apply 3D visualization and modelling techniques in data interpretation, and (3) improve the structural database on the most important mineral resource provinces in Finland. In compiling models of the HIRE targets we have used reflection seismic data, airborne and ground geophysics, geological maps and drilling data.

Reflection seismic surveys yield high resolution structural information of the upper crust with a cost-effectiveness and resolution not achievable by any other geophysical method. The petrophysical parameters underlying rock reflectivity, i.e., the acoustic impedance, which is a product of rock density and seismic velocity, are closely associated with geological rock properties.

The list of survey targets comprises 15 exploration and mining camps in a very diverse selection of geological environments containing Cu, Ni, Cr, PGE, Zn, and Au deposits, most of them economic, as well as the first Finnish site for nuclear waste disposal. The surveys were carried out in co-operation with 12 industrial partners. Fieldwork was completed in 2007–2008, and processing and interpretation in 2009–2010. The surveys comprised 2D lines measured using either Vibroseis sources or dynamite shots in shallow drill holes. Typically, a target area was covered by a network of connected lines with a total length of 10–90 line km, which provided a good basis for 3D visualization and modelling (Fig. 1). The seismic contractor was Vniigeofizika, Moscow, Russia, responsible for the field acquisition and basic processing of the data. The Institute of Seismology, University of Helsinki, has been the research partner and subcontractor in the project and responsible for the more detailed post-stack processing of the results.

Previously unknown structures were revealed in all HIRE targets, and our database on the structures of the investigated deposit areas has expanded considerably. Furthermore, previously unknown potential host rocks of deposits were discovered in several targets. The HIRE results have considerably increased the level of detailed knowledge at previously unexplored depths and it seems that the ore potential of the study areas may be higher than previously anticipated. The results justify the continued application of seismic reflection surveys in mineral exploration.

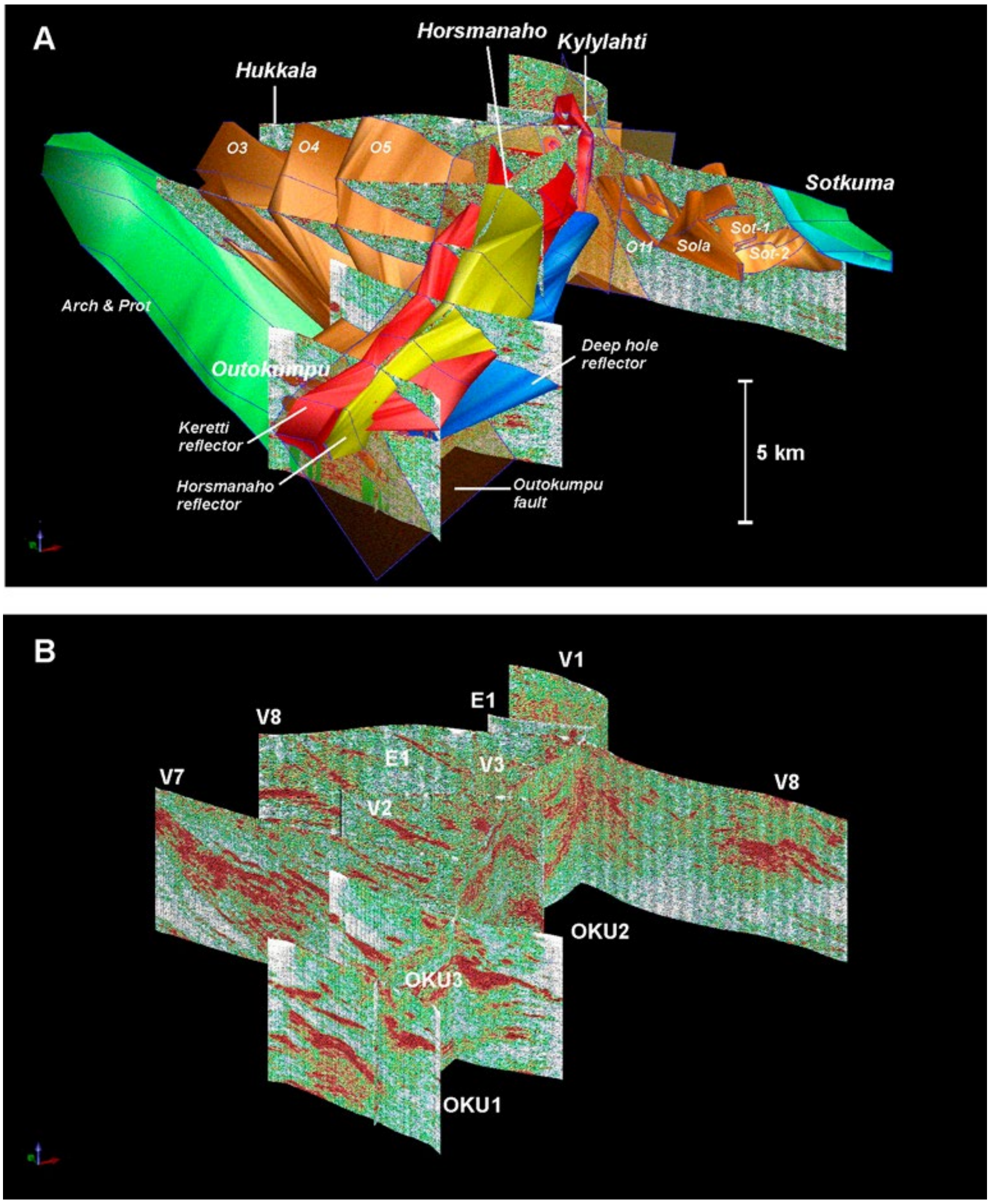

Fig. 1. An example of HIRE results and their 3D modelling in the Outokumpu Cu-Co-Zn ore belt. View of the ore belt from the south showing the seismic sections as a fence diagram and the constructed 3D bodies of the major reflective units.

Cu AND S ISOTOPIC FINGERPRINTING OF FINNISH ORE DEPOSIT ENVIRONMENTS USING LA-MC-ICPMS ON THIN SECTIONS

by

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The stable isotopic composition of sulfide minerals, co-genetic to the formation of some selected Finnish ore deposits, has been determined using a Nu Plasma Instruments multi collector-ICP-MS and a laser ablation system. Metal isotope (Cu, S) geochemistry studies of ore-forming systems from individual sulfide phases may shed some new light into the temperature and redox changes that are responsible for the precipitation of the mineralizing fluids leading to the formation of economic deposits. The source of the mineralizing fluids can also be traced using the S isotopic compositions of the sulfides.

Sulfides have been sampled in three main types of ore deposits: 1) Palaeoproterozoic volcanogenic massive sulphide (VMS) Cu-Zn deposits: Pyhäsalmi Cu, Zn, (Au) ore in central Finland. Ore minerals are dominantly pyrite, sphalerite, chalcopyrite ± pyrrhotite. 2) Palaeoproterozoic orogenic gold deposits from the Central Lapland greenstone belt: A – Suurikuusikko (Kittilä mine). 95% of the gold occurs in arsenopyrite and As-rich pyrite. Chalcopyrite is also present in minor abundances. B – Iso-Kuotko. The gold mineralization is related to a series of sulfide-rich quartz-carbonate veins. 3) The Keivitsa Cu-Ni magmatic sulfide deposit within a Palaeoproterozoic mafic-ultramafic intrusion in central Lapland.

Copper and sulphur isotope analyses were performed using a Nu Plasma HR multicollector ICP-MS at the Geological Survey of Finland in Espoo together with a Photon Machine Analyte G2 UV laser. Sulphur isotopes (^{32}S, ^{34}S) were analyzed at medium resolution. The sample was ablated at a spatial resolution of 65 μm. Two in-house chalcopyrite standards were used for external standard bracketing and quality control. For a $\delta^{34}S_{CDT}$(‰) value of -1.00(‰), we have found an average value of -1.01 ± 0.37‰ (n = 20). The Cu isotopes (^{63}Cu, ^{65}Cu) were analyzed at low resolution. Samples were ablated at a spatial resolution of 20 μm. Two in-house chalcopyrite standards were used for standard bracketing and quality control. For a $\delta\,^{65}Cu$ (‰) value of -0.15(‰) we have determined an average value of -0.16 ± 0.17‰ (n = 16). The use of a matrix-matched standard is critical for accurate results.

Our preliminary analytical results for the three ore types are shown in Fig. 1. The copper isotopic composition of sulfides does not fingerprint a specific type of ore deposit. The isotopic heterogeneity within a thin section is, in some cases, greater than the difference in isotopic composition between two different types of ore deposits. In contrast, sulfur isotopic composition of sulfides is a potentially powerful tracer of the interaction between magmatic and sedimentary sources and thereby providing unique deposit-specific genetic information.

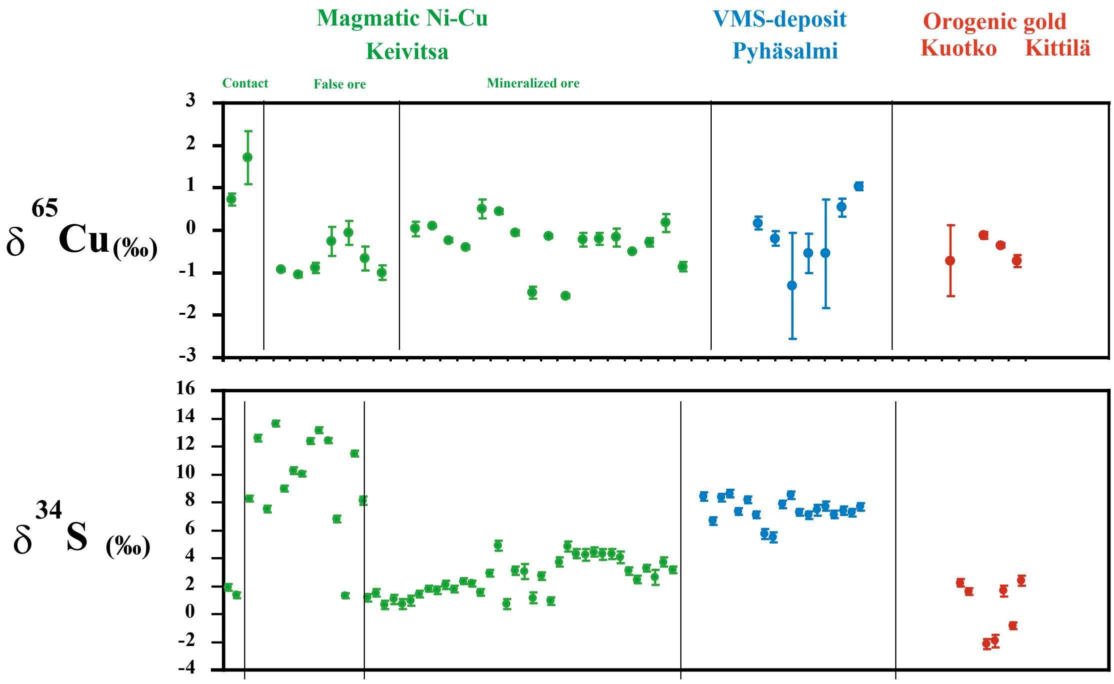

Fig. 1. Copper and sulphur isotope compositions of sulphides in different ore types.

ARCHEAN-PROTEROZOIC BOUNDARY IN THE CENTRAL PART OF FENNOSCANDIAN SHIELD REVISITED

by

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The western margin of the Karelian Province in central Finland shows evidence of rifting and lithosphere thinning from 2.1 to 1.95 Ga but it is still uncertain whether cratonic breakup occurred at 2.06 Ga in a volcanic regime, at 1.95 Ga in a non-volcanic margin, or that breakup in a volcanic margin setting at 2.06 Ga was followed by rifting in a non-volcanic margin setting at about 1.95 Ga. Proposed tectonic models for the Archean-Proterozoic (AP) cryptic suture include continent – continent/arc collision (about 1.9 Ga) between the Archean craton and a Paleoproterozoic microcontinent-arc collage, back-arc/retro-arc basin or an accretion of arc terranes within a strike-slip regime. An early thin-skinned E- to NE-vergent fold and thrust belt was apparently superimposed by later thick-skinned thrusting involving cratonic foreland basement. The high-grade psammites, pelites and amphibolites northwest of Kuopio and west of exposed Archean rocks have been generally considered as Svecofennian, with the inferred suture with the cratonic foreland to the east being considered steep. New data (by Lahtinen, Lahaye, Huhma, Kousa and Luukas) indicate that these rocks can be considered as Kalevian, at least in terms of age, and that they would have been deposited on the lower plate after c. 1.94–1.91 Ga. This would place the concealed Archean boundary some 30–70 km further west than in most interpretations. No fold and thrust belt-related foredeep to foreland basin sequences have been noticed before but new data (Lahtinen, Huhma, Lahaye, Johanson, Kohonen and Kontinen) indicate that some pelitic and psammitic rocks in the Koli-Kontiolahti area, which were deposited after 1.92 Ga, are potential candidates for such sequences. It is postulated that during the initial stages of continent – continent/arc collision, slab breakoff facilitated pathways for deeper mantle-derived magmas, seen as 1.92–1.90 Ga mafic volcanism in the lower plate. Continuous mafic magmatism caused crustal melting and during subsequent contraction, in a transpressional environment, large amounts of mafic and felsic magmas at 1.89–1.88 Ga intruded along the AP boundary into already thickened crust. As a result of these superimposed collisional events a complex tectonic intercalation (reminiscent of so-called crocodile jaw geometry) of Archean continental to Paleoproterozoic continental and arc crust and mantle formed. Mantle-derived magmas from different sources intruded at 1.88–1.85 Ga but waning magmatic (mainly felsic) and localized tectonic activity continued until c. 1.78 Ga. Some lateral displacement along the suture is evident but these new data favour continent – continent/arc collision as the main cause for the observed lithosphere structure in the Archean-Proterozoic boundary in the central part of the Fennoscandian Shield.

UNCERTAINTIES RELATED TO 3D GEOPHYSICAL INVERSION – THE VIHANTI AREA AS AN EXAMPLE SITE

by

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The Vihanti area belongs to the Palaeoproterozoic Vihanti−Pyhäsalmi Zn-Cu-Pb zone, which is located along the northeastern margin of the Svecofennian Domain. Ore deposits at Vihanti are of volcanogenic massive sulphide (VMS) or replacement type and are confined to a volcano-sedimentary schist association. Topographically, the Vihanti represents an ancient peneplane covered with swamps and ridges, as a result of which there are very few natural bedrock exposures. In the present study, constrained and unconstrained magnetic and gravity inversions are tested in the Vihanti area. The magnetic anomalies are associated with the Lampinsaari and Kuuhkamo Zn deposits, while the in addition, ore-hosting skarn-banded felsic rocks, cordierite gneisses and mafic volcanics are denser than the surrounding intermediate metatuffites. Magnetic data acquired during a helicopter electromagnetic VTEM survey (terrain clearance about 70 m) and ground gravity data are processed using the GRAV3D and MAG3D inversion codes developed by the University of British Columbia (UBC) (e.g. Li & Oldenburg 2000). The inversion was constrained by the geological map (Kousa & Luukas 2004), drill hole data and geological 3D model derived from HIRE seismic sections (Kukkonen et al. 2011). However, the magnetic susceptibility distribution does not follow lithological boundaries and is therefore difficult to tie in with the geological data. Furthermore, susceptibility values vary over short distances and have a highly skewed distiribution, making it very difficult to build an initial voxel model from susceptibilities using rock type distiribution. In addition, only mafic rocks and skarns differ clearly with respect to density from the other rock types in the area. Because of the lack of data, there are several possible initial geological models for inversion. It was also concluded that the initial models should be very simple. Different initial models lead to very different density and susceptibility distributions. On the other hand, unconstrained inversion without any geological information gives an objective starting point for the geological 3D modeling.

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THE MYTH OF "THE 1.8 GA CENTRAL LAPLAND GRANITOID COMPLEX" UNRAVELS INTO DISCRETE MAGMATIC EVENTS DURING A 350 MA PERIOD FROM 2.13 GA TO 1.76 GA

by

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INTRODUCTION AND HISTORY

The Central Lapland granitoid complex (CLGC) covers an area of about 10 000 km^2 in southern and central Lapland. Being surrounded by Proterozoic greenstone belts with significant ore potential, the granitoid complex has largely been neglected in terms of mapping and exploration efforts. Mikkola (1941) wrote the first geological description of the northern part of the complex, where he divided the granites into older, migmatitic granites and younger Nattanen-type granites that showed discordant cross-cutting relations with all other rock types. Lauerma (1982) sampled some outcrops in the Rovaniemi and Kemijärvi areas for U–Pb dating of zircon, monazite, and titanite. Based on the rather imprecise bulk TIMS age results he assigned the CLGC to the late Svecokarelian (Proterozoic) group with an age of about 1.80 Ga. However, he did mention that further geological mapping and isotopic studies were needed to constrain the age and geological evolution of the complex.

The next step in dating the granites of Lapland was taken by Huhma (1986), who included several granite samples from the CLGC in his study. Although the Nattanen-type granites were confirmed to be ca. 1.77 Ga in age, two other samples (A145 Molkokongäs and A748 Iso Nilipää) gave contrasting results, being 1843±23 Ma and 2136±16 Ma in age, respectively. Both granite plutons were later re-sampled and analyzed (several times in the case of Iso Nilipää) with both TIMS and SIMS and their ages were confirmed to be the same within error with both methods, Molkokongäs revealing an ion probe concordia age of 1855±13 Ma and Iso Nilipää an age of 2126±5 Ma (Rastas et al. 2001, Ahtonen et al. 2007). Rastas et al. (2001) analyzed a granodiorite cross-cutting the supracrustal rocks on the northern side of the CLGC and obtained an age of 1914±3 Ma. Väänänen and Lehtonen (2001) studied the northwestern margin of the CLGC and although they did not analyze any samples from the granitoid complex proper, they confirmed the presence of 1.88 Ga Haparanda-type intrusions in the area, as well as younger granites with an age of 1805±10 Ma.

Mutanen (2003) described a suite of appinitic intrusions within the CLGC and Väänänen (2004) published an age of 1796±4 Ma for the Tainio gabbro, which belongs to the appinite suite. Ahtonen et al. (2007) published several new analyses from different sub-units of the CLGC, including another appinite (A1714 Jääskö), which gave an age of 1796±3 Ma. The main focus of the study by Ahtonen et al. (2007) was done in the eastern part of the CLGC, where they reported the presence of another 2.12 Ga old granodiorite (the Tohmo intrusion) and published several new granite ages, which ranged from 1.81 Ga (Pernu granite) to 1.79–1.76 Ga.

Nironen (2005) presented a new classification for Proterozoic orogenic granitoid rocks in Finland in which he divided the CLGC into synorogenic (Haparanda-type, 1.89–1.86 Ga), late orogenic (main part of the CLGC, 1.84–1.86 Ga) and postorogenic granitoids (Nattanen-type, 1.80–1.77 Ga). However, based on the data on the eastern part of the CLGC, Ahtonen et al. (2007) challenged the classification, as tectonic movements were still ongoing in eastern CLGC while the postorogenic phase was reached in the northern part of the area.

NEW DATA AND DISCUSSION

The eastern part of the CLGC was mapped in 2008–2010 by the GTK and during the course of mapping 14 new geochronological samples were collected, five of which represented different granite phases of the GLGC. Based on the results (L. S. Lauri, unpublished), at least the eastern part of the CLGC may be divided into three sub-areas. The 1.81 Ga Pernu-type granites of Ahtonen et al. (2007) seem to be restricted to the northeastern corner of the Archean Pudasjärvi complex, from which they most probably were derived by partial melting. They are separated from the ca. 1.79–1.77 Ga Jumisko-type granites (Ahtonen et al. 2007) by the Ailanka fracture zone (Airo & Ahtonen 1999), which may represent a crustal-scale tectonic boundary. It may be speculated whether the Pernu-type granites could represent northward movement and collision of the Pudasjärvi complex with the Central Lapland block. In addition to the Pernu-type and Jumisko-type granites the eastern part of the CLGC contains a late, undeformed granite phase, the age of which is between 1.77–1.76 Ga. These Kellastentunturi-type granites occur on both sides of the Ailanka fracture zone and, despite their ages being similar to those of the Nattanen-type granites, they represent a different granite type both in terms of geochemistry and intrusive style.

The third sub-area is found at the northern margin of the CLGC, in the transition zone to the Central Lapland greenstone belt (CLGB), where Ahtonen et al. (2007) described the 2.12 Ga Tohmo granodiorite. A new granite sample from the Varsatunturi hill, some 20 km NW of Tohmo gave an age of 2118±13 Ga (L. S. Lauri, unpublished). These 2.1 Ga intrusions seem to flank the margin of the CLGB from the Kemijärvi area (Varsatunturi, Tohmo) up to the Kittilä area (Nilipää), forming a separate zone at the margin of the CLGC. In addition, there are indications of even older, 2.3 Ga granitoids in the same zone (J. Räsänen, pers. comm.).

New age data are also available from the southern margin of the CLGC west of the town of Rovaniemi, where the majority of the granites seem to belong to the younger. 1.77 Ga age group (L. S. Lauri, unpublished). However, some deformed porphyritic granites gave an age of ca. 1.98–1.99 Ga, which is similar to the supracrustal Korkiavaara formation (Hanski et al. 2005). Further research is needed to constrain the tectonic significance and geochemical character of the 1.98 Ga event.

Based on published and new data the CLGC seems to comprise at least six (if not more) different intrusion events extending in age from 2.13 Ga to 1.76 Ga. The concept of a uniform 1.8 Ga old granite complex is obsolete. However, the remark by Lauerma (1982), that further geological mapping and isotopic studies are still needed to constrain the age and geological evolution of the complex, remains relevant.

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USE OF HANDHELD GAMMA-RAY COUNTERS IN PROSPECTING FOR U AND Au DEPOSITS

by

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Of the naturally occurring radioactive elements K, U and Th, the decay series of U-238 and Th-232 contain daughter nuclides that emit gamma-rays when they decay. Portable devices such as Geiger counters, scintillometers and spectrometers may be used in the field to detect this radioactivity.

Hand-held gamma-ray counters have been used in prospecting for radioactive boulders and outcrops since the 1930's. Although instrument technology has improved in recent years, particularly through the availability of self-calibrating spectrometers with Bluetooth GPS connections, the method has remained essentially the same as described by Huhma (1966). Field target selection may be based on geological or aeroradiometric criteria. The field crew is then sent to the site with portable counters to locate the source for the radioactivity. Depending on the amount of radioactive minerals in the rocks, buried anomalous samples may be detected at depths of up to 50 cm. The boulders and outcrops found may then be sampled for further petrographic and geochemical studies.

The two main types of gamma-ray counters in use are scintillometers and spectrometers. A scintillometer registers the spectrum of gamma radiation as total count readings (counts per second), hence it cannot detect whether the radiation is caused by K, U or Th. Being relatively cheap and light-weight the scintillometer is a useful field device for greenfield prospecting. It detects the radioactive targets, which may then be sampled for further studies. A spectrometer is a device which measures separately the gamma-rays caused by the decay of K, U and Th and, on the basis of peaks accumulating in characteristic spectral windows, calculates the equivalent concentrations of the three radioactive elements in addition to the total radioactivity measured. The spectrometer, although being a heavier and more expensive tool than the scintillometer, is more useful in the field, as the prospecting activities may be targeted for a specific element, ignoring the anomalies caused by other elements. A spectrometer may also be used in the field base camp for screening the samples found with a scintillometer. Modern devices also give readings of external gamma radiation dose rate to be used for radiation safety and environmental studies.

The use of hand-held gamma-ray counters in prospecting for uranium deposits is self-evident; however, the method may also be applied to gold exploration. Au and U are commonly transported together in ore-forming processes and many Au occurrences contain marked concentrations of U (see e.g., Vanhanen 2001). Radioactive targets may easily be located in the field and used as a proxy for Au to locate the most prospective zones for subsequent more expensive and time-consuming chemical analyses.

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MAIN GEOLOGICAL FEATURES OF THE KUOPIO DISTRICT

by

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INTRODUCTION

Geologically the Kuopio district is part of the transition zone between the Svecofennian domain and the Archean craton known as Raahe–Ladoga zone and includes a variably preserved cover sequence (Karelian domain) overlying the Archean basement rocks. The transition zone is interpreted as a geosuture characterised by NW–SE- and N–S-trending faults and shear zones, an extensive gravity minimum and high-grade metamorphic blocks (Koistinen 1981, Korsman et al. 1988). Bedrock mapping for the GTK 1:100 000 series has been undertaken in the much of the Kuopio district in recent years (Lukkarinen 2000, 2002, 2008, Pääjärvi & Äikäs 2005, Äikäs 2000), followed by ongoing revision and definition of rock units for the national stratigraphy database (FINSTRATI) and the nationwide seamless bedrock map (Bedrock of Finland – DigiKP).

ARCHEAN CRATON

The Archean bedrock in the Kuopio district consists of the southernmost parts of the Iisalmi and Rautavaara complexes as well as numerous discrete gneiss domes (Kuopio, Rytky, Vehmasmäki, Paukarlahti, Kotalahti, Konnus and Saamainen) and tectonic slices to the west of the domes, making up the Kuopio Complex; these domes and slivers are surrounded by Paleoproterozoic supracrustal rocks.

The Kuopio complex is bounded by the dextral Suvasvesi D3–D4 faults and shear zones in the east and the Airaksela D3–D4 fault in the west (Forss et al. 1999). A possible connection between the Iisalmi and Rautavaara complexes and the domes of the Kuopio Complex is under discussion, as the recognition in the Kuopio Complex of both the sanukitoid-type granodiorites similar to those of the Rautavaara complex and quartz diorites/enderbites resembling those of the Iisalmi complex suggests that the Kuopio Complex may represent a disrupted and deformed part of the other two complexes. In addition to the sanukitoids and quartz diorites, the Archean bedrock displays typical high grade, variably migmatized and retrograde gneisses, both paragneisses and orthogneisses.

The northwards-trending, 16 km long and 1.5 km wide linear Siilinjärvi carbonatite-glimmerite complex (2610±4 Ma) and related syenites intruding the boundary between the Iisalmi and Rautavaara complexes are a rare example of Archean alkaline magmatism, possibly reflecting the earliest extension of the Archean crust.

SUPRACRUSTAL ROCKS OF THE KARELIAN DOMAIN

The Paleoproterozoic supracrustal rocks represent the metamorphic counterparts of epicontinental sediments: arkosites/conglomerates, quartzites, carbonate and calc-silicate rocks, black schists, and metabasaltic volcanic rocks deposited and erupted on the Archean basement. Mica schists and mica gneisses represent metamorphosed clays and sands deposited on the ocean floor.

Arkosites, originally quartz- and feldspar-rich sands are the lowermost deposits overlying the Archean basement. Some of the arkosite deposits contain conglomerate intercalations, typically with well-rounded pebbles, predominantly granitic in composition and varying in diameter from a few centimetres up to 0.5 m. The quartzites, originally deposited as quartz sands, overlie the arkosites. Due to metamorphic recrystallization and deformation, the quartzites rarely show primary structures. In places the quartzites contain reddish K-feldspar spots due to potassium metasomatism. The best- preserved quartzite deposits occur in the Nilsiä quartzite belt, where the thickness of the formation may exceed 1000 m. In the Kuopio area narrow, up to 200 m thick quartzite units flank the domes of the Kuopio complex. Small quartzite deposits have also been found adjacent to most of the basement gneiss slivers.

Based on a recently obtained isotopic age determination (2190±10 Ma; Hanski et al. 2010) from the nearly concordant Rahasmäki sill inturding the Nilsiä quartzites it is possible to correlate the arkosite -conglomerate deposits with the chronological Sariola unit (2550–2300 Ma) and the quartzites with the Jatuli units (2350–2100 Ma) in the Kuopio district.

The carbonate rocks are mainly dolomitic or calcite-bearing dolomites, whereas calcitic carbonate rocks are less common. Calc-silicate rocks and chert occur as interbeds. The carbonate deposits are rather small, and often associated with quartzites and mafic metavolcanic rocks. Thin phosphatic interbeds containing uranium have been found within the carbonate sequence in the Siilinjärvi and Juankoski districts and in some places, pyrite- and graphite-rich black schists have been observed.

Volcanic rocks are variably preserved and usually occur together with the quartzites and carbonate rocks. The most prominent metavolcanic formations are situated in the Siilinjärvi and Kuopio areas. The volcanic formation at Siilinjärvi contains three mafic members and one felsic member. The mafic metavolcanics are mainly pillowed or massive metalavas although sporadic pyroclastic intercalations are present. The rocks of the felsic member are pyroclastic ash-flow tuffs or ignimbrites in origin. The metavolcanic rocks consist of porphyritic, massive and pillowed basaltic metalavas; pyroclastic rocks are rare. Interstices of pillow lavas are filled with calc-silicate material, so the more deformed types look like diopside-banded amphibolites. In places, metachert intercalations up to 10 m thick occur in the metalava flows. Based on the age (2062 Ma) of the felsic metavolcanics of the Koivusaari formation the metavolcanic rocks and underlying carbonate rocks of the Kuopio complex are correlated with the chronological Marine-Jatuli unit (2100–2060 Ma).

The mica schists and mica gneisses of the Karelian domain in the Kuopio area are assigend to the Lower-Kaleva (2060–1950 Ma) in a chronological sense. These originally turbiditic pelites and clay-rich graywacke sands have been variably metamorphosed and contain sillimanite, cordierite and garnet. In places, well-preserved sedimentary structures such as graded bedding and convolute bedding are displayed, but migmatitic variants with stromatic or phlebitic trondhjemite veins are also present.

SUPRACRUSTAL ROCKS OF THE SVECOFENNIAN DOMAIN

The supracrustal rocks between Kuopio and Suonenjoki belong to the Svecofennian domain. The main rock types are mica schists and mica gneisses of the Lempyy suite bounded in the west by the Iivesi fault and in the east by the N–S-trending overthrust zone situated east of Leppävirta. The relationship between the lithologies of the Lempyy suite and the Viinijärvi suite east of the overthrust is under discussion. The sedimentary rocks of the Lempyy suite were originally turbiditic pelites and clay-rich graywacke sands. Small calc-silicate concretions are common in these rocks. In places primary sedimentary structures are well preserved, but often the gneisses are migmatitic with stromatic or phlebitic granodiorite or trondhjemite veins. Migmatic gneisses with schollen structure are present within the Airaksela fault zone. As a result of metamorphism under upper amphibolite-facies, almost granulite-facies conditions, psammitic mica gneisses contain garnet porphyroblasts, whereas sillimanite and cordierite are typical of pelitic gneisses. Sporadic kyanite porhyroblasts in gneisses at the Airaksela fault zone indicate medium pressure metamorphism, and the feldspar crystals 4–5 mm in size overprinting earlier microstructures indicate polyphase deformation processes within this tectonic zone.

Within the schists and gneisses of the Lempyy suite there are variably sized belts of hornblende gneiss and amphibolite. The rocks are mafic and intermediate lavas and tuffs in origin, though volcanic structures are rarely preserved. In places the alteration of the hornblende-bearing material and pelitic material indicate a tuffitic origin. The metavolcanic rocks are commonly migmatized by granitic or trondhjemitic veins.

West of the Iisvesi fault zone, near Suonenjoki, certain mica gneisses associated with mafic, intermediate and felsic volcanic rocks and surrounded by granodioritic and tonalitic intrusions are correlated with the Vihanti and Pyhäsalmi groups, whose age is about 1930–1900 Ma old (i.e. older Svecofennian).

Further south, the western side of the Iisvesi fault zone consists predominantly of well preserved metagreywackes with thin conglomerate interbeds and partly of migmatic mica gneisses (Rusalansuo lithodeme).

INFRACRUSTAL ROCKS

Most of the Paleoproterozoic plutonic rocks in the western part of the Kuopio district are K-feldspar and plagioclase porphyric granitoids that range in composition from granite to quartz diorites. These granitoids typically contain enclaves of mica schist and small roundish calc-silicate concretions. Even-grained granites and granodiorites are rare. Even-grained intermediate (quartz diorite and tonalite) and mafic plutonic bodies (gabbro and diorite, including the nickel-bearing bodies in the Kotalahti dome) are relatively small in size. These plutonic rocks are related to the Central Finland granitoid complex, having zircon U/Pb-ages of about 1890–1880 Ma.

West of Siilinjärvi and Kuopio, banded or gneissose tonalites and granodiorites with remnants of mica gneisses and metavolcanic rocks, are located between the Central Finland granitoid complex and the Archean gneiss complex. There are also zones of nebulitic (diatexite) gneisses with mica gneiss and metavolcanic rock relicts, indicating a sedimentary-volcanogenic origin for these gneisses. It is conceivable that the nebulitic gneisses could be correlated with the gneisses of the Lampaanjärvi suite to the north of the Kuopio district and also with the Lempyy suite.

The rocks of the eastern part of the Kuopio district are related to the Heinävesi intrusive suite. The composition of the felsic rocks varies from granite to tonalite. Mafic rocks are mainly quartz diorite and gabbro in composition. Within the granitic rocks both even-grained and porphyritic varieties occur; based on the contact relations the latter are older. The Pajulahti syenite intrusion between the Siilinjärvi carbonatite complex and the Nilsiä quartzite belt yields a sphene age of 1860 Ma.

Several granitoids related to the Suvasvesi fault zone have U-Pb zircon ages close to 1870 Ma (Huhma 1986, Lukkarinen 2008); of these intrusions the Heinävesi granodiorite and the Juurus tonalite also contain quartz dioritic and dioritic variants. The Juurus tonalite in particular shows inclusions and remnants of the surrounding mica gneisses indicating an anatectic origin.

DYKE ROCKS

Gneisses and granitoids of the Archean craton are intruded by metadiabase dykes, often metamorphosed and deformed into amphibolites. The width of the dykes varies from a few centimetres to several metres and in some outcrops, arrays consisting of several dykes have been observed. The ages of these metadiabase dykes varies from 2300 Ma to 2100 Ma. In the western part of the Kuopio district some well-preserved ophitic metadiabase dykes also intrude the mica gneisses.

The Archean craton and the overlying Paleoproterozoic rocks are cut by a texturally, structurally, and compositionally varying series of intermediate rocks, provisionally referred to as microtonalites (Huhma 1981). The microtonalites occur mainly as dykes but also as larger intrusions in a relatively narrow zone west of line drawn between Leppävirta–Tuusniemi–Kaavi to an area west of Oulujärvi (Rautiainen 2000). Scattered observations of these dykes have been recorded still further to the south and southeast, from Juojärvi, Kangaslampi and Virtasalmi.

Dating of this intermediate magmatism has been problematic, mainly due to contamination. According to Huhma (1981), the microtonalite dykes postdate the 1860 Ma Maarianvaara granite intrusion, but predate the lamprophyre dyke swarm of ca. 1785 Ma in the Nilsiä and Kaavi area (Kietäväinen 2009, Woodard 2010).

There are also many granitic to granodioritic and trondhjemitic dykes intruding the metasediments; most of the granitic dykes are pegmatitic in appearance and grain size.

METAMORPHIC AND TECTONIC FEATURES

The Archean rocks have experienced polyphase metamorphic and deformation events under amphibolite/granulite-facies conditions during the Archean and again during Proterozoic time. The Paleoproterozoic rocks have mainly been metamorphosed under amphibolite-facies conditions. However, based on the Mg-Fe contents in the cordierite-garnet and biotite-garnet mineral pairs, there are zones where the pressure and temperature of the metamorphism have been reached the granulite-facies (Lukkarinen 2008).

The present lithological features of the Archean and Paleoproterozoic rocks in the Kuopio district are a result of the deformation processes that occurred 1910–1800 Ma ago as several successive folding, overthrusting and faulting events, with at least four deformation phases recognized in the Paleoproterozoic rocks (Forss et al. 1999).

NEOPROTEROZOIC MAGMATISM

The Eastern Finland Kimberlite Province comprises twenty Neoproterozoic to Paleozoic intrusive bodies, mostly kimberlitic diatremes but also hypabyssal kimberlites, with mineralogy typical of Group I kimberlites. Major elements compositions show that the kimberlites are variably altered and/or contaminated, mostly by granitoid material (O'Brien & Tyni 1999). Almost all of the kimberlites contain at least trace amounts of microdiamonds, and one of the pipes is currently under mining development.

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THE MAJOR PALAEOPROTEROZOIC (1.93–1.92 Ga) VMS-DEPOSITS IN THE NORTHWESTERN RAAHE–LADOGA ZONE, CENTRAL FINLAND

by

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The Palaeoproterozoic bedrock within the north-western part of the highly tectonized and metamorphosed NW-trending Raahe–Ladoga Zone (RLZ) (Fig. 1) consists of Svecofennian (1.95–1.80 Ga) rocks between the Archaean (3.1–2.6 Ga) basement complexes in the east and the Central Finland Granitoid Complex (1.88 Ga) in the southwest. The Vihanti–Pyhäsalmi district in this part of the RLZ has been one of the most significant base metal mining areas in Finland since the 1950's.

The Palaeoproterozoic volcanic-sedimentary Pyhäsalmi group contains one large and several smaller VMS type deposits in the Pyhäsalmi–Kiuruvesi area. The large Pyhäsalmi massive Zn-Cu-pyrite deposit, with a total reserve,(mined out plus current reserves) of 57.9Mt @ Cu 0.95%, Zn 2.41%, S 37.5%, Au 0.4g/t and Ag 14g/t (T. Mäki, pers. com, 2012), is situated in a bimodal volcanic sequence, characterized by an extensive (metamorphosed) sericite-cordierite-anthophyllite alteration zone. The massive ore was originally hosted entirely by altered felsic and mafic volcanic rocks, but the deep parts of the ore have been separated from the upper part by fault/shear zones, as a consequence of which the deep ore is now juxtaposed against unaltered felsic and mafic volcanic rocks, with sharp and mylonitic contacts.

There are three minor satellite VMS deposits in the vicinity of the Pyhäsalmi ore, which have been mined out during the operation of the Pyhäsalmi mine. The Ruostesuo deposit in the Kiuruvesi area (mined 1988–1990, 0.24 Mt @ 2.63% Zn, 0.3% Cu, 8 ppm Ag, 0.3 ppm Au, Finzink) and Kangasjärvi deposit in the municipality of Keitele (mined 1988, 0.086 Mt @ 5.12% Zn, 0.06% Cu, 41 ppm Ag, Finzink) have host rock and alteration assemblages similar to those of the Pyhäsalmi ore. The Mullikkoräme deposit (mined 1990–2000, 1.15 Mt @ 6.0% Zn, 0.2% Cu, 0.7% Pb 50 ppm Ag, 0.9 ppm, Finzink), which is situated 8 km NE of Pyhäsalmi, differs slightly from the Pyhäsalmi ore due to its higher Zn and Pb content and also in that the host rock assemblage has relatively more calcareous host rocks. In these respects Mullikkoräme is more reminiscent of the Vihanti-type ore deposits.

Other important mineralizations include the Cu-rich deposit at Säviä in the Pielavesi district, the Kaskela and Vuohtojoki mineralizations at Kärsämäki and

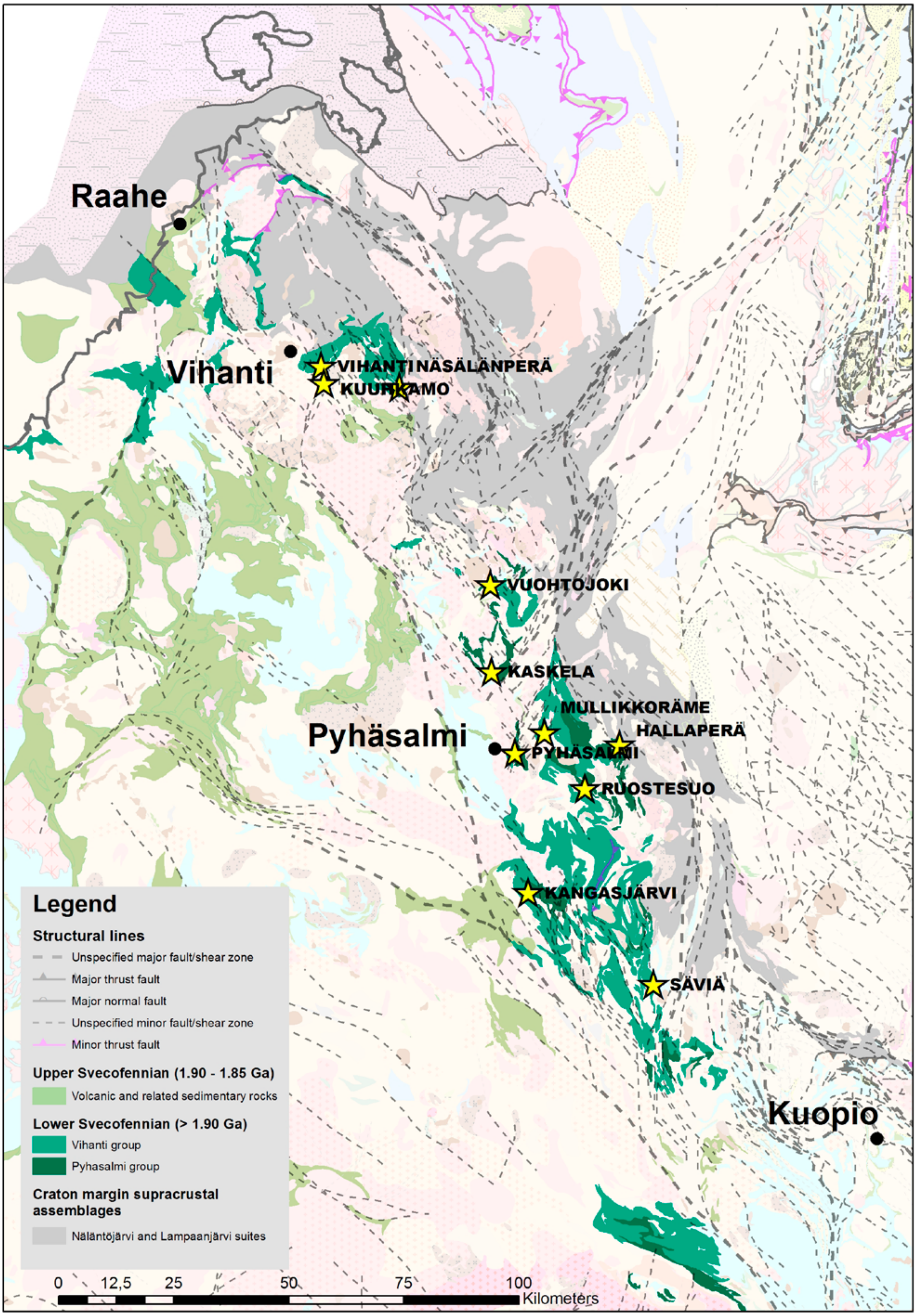

Fig.1. Location of the major VMS deposits and mineralizations in the RLZ. Map generalized from the Bedrock of Finland – DigiKP base (referred 30.03.2012).

the Hallaperä mineralization in the municipality of Kiuruvesi. The Säviä deposit is situated in mafic to intermediate volcanic rocks of the Pyhäsalmi type. Kaskela deposit is hosted by altered felsic volcanic rocks fringing the subvolcanic Venetpalo dome. The highly remobilized and sheared Hallaperä and Vuohtojoki mineralizations are related to Pyhäsalmi type felsic volcanic rocks but in lithological environments that seem to lack any significant associated mafic volcanic rocks.

The Vihanti massive Zn-Cu-Pb deposit (mined in1954–1992, 28 Mt @5.12% Zn, 0.48% Cu, 0.36% Pb, 25 ppm Ag, 0.49 ppm Au, Finzink) is situated in a sequence which is dominated by intermediate to felsic volcanic rocks and in which mafic volcanic rocks are scarce. The massive ore is hosted in a calcareous felsic volcanic to sedimentary horizon adjacent to an altered (metamorphosed/cordierite-sillimanite) quartz porphyry sill. Recent studies indicate that the ore has formed by replacement processes closely related to emplacement of the subvolcanic felsic intrusion.

The nearby Näsälänperä, Kuuhkamo and Kokkoneva mineralizations resemble the Vihanti deposit. First, all these three deposits occur at about the same stratigraphic level as Vihanti in the Vihanti group. Second, each of these deposits have a close spatial association with altered quartz-feldspar porphyry sills in the hosting calcareous felsic volcanic rocks and dolomites. The porphyry sills were probably essentially to hydrothermal mineralizing processes as sources of both heat and metals (Kousa & Luukas 2004).

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GEOPHYSICAL LABORATORY MEASUREMENTS OF ORE FORMATIONS

by

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Geophysical laboratory measurements of mineralized samples and ores at the Southern Finland office of GTK are used in both regional scale studies and for detailed investigations. The measurements have three main objectives. Firstly, the purpose is to obtain petrophysical data from mineralization and ore bodies under investigation in order to provide information for ongoing exploration. Sampling locations for petrophysical measurements are selected utilizing airborne geophysical data. It is planned that in future, petrophysical measurements will be systematically made on drill cores obtained from exploration targets, as is currently done in the Northern Finland office of GTK. The second objective is to obtain material for petrophysical classification of different mineral deposit types, and to find critical physical parameters for their characterization. Thirdly, detailed investigations are made at outcrop scale to delineate differences in petrophysical properties between ore and host rocks, with the aim of identifying and characterizing possible alteration processes that might be reflected in the physical properties of rocks. These detailed studies also include studies on magnetic structures (AMS).

The principal petrophysical parameters measured are magnetic susceptibility, remanent magnetization (NRM) and density. In addition, the number of conductivity measurements of ore deposits has increased and is expected to attain greater importance in future studies. Measurements of anisotropy of magnetic susceptibility (AMS) also form an essential part of current research and magnetic mineralogy is also determined during different rock magnetic investigations.

In 2011 geophysical laboratory measurements were carried out on three drill cores from the Uunimäki gold deposit and results were correlated with geochemical data. During the 2011 field season, oriented samples were taken from Uunimäki, Kedonojankulma and Mäyrä occurrences. In addition to these, nine occurrences in southern Finland were sampled, partly for checking against aeromagnetic anomalies, and partly for ore prospecting purposes. In the Uunimäki gabbroic occurrence, the highest magnetization values (both susceptibility and remanence) and conductivities correlate with strong IP anomalies. In these rocks the magnetic mineral is monoclinic pyrrhotite. The lowest magnetization values are found among weak IP anomalies, where the magnetization is carried by magnetite, in addition to small amounts of pyrrhotite. Another site near Uunimäki is

Kantola, which shows a strong magnetic anomaly, carried by both magnetite and pyrrhotite; this site ought to be studied more thoroughly. At Kedonojankulma the typical magnetic mineral within the plagioclase quartz porphyry is monoclinic pyrrhotite. The magnetization values increase slightly within the hydrothermal shear zone, and the Q values are highest within the shear zone, indicating the dominance of remanent magnetization over induced magnetization. At Mäyrä, where gabbro samples were taken from a profile across a shear zone, the situation is quite the opposite, as the magnetization values are much lower compared with those in the host gabbro; in this case, the magnetic mineral in the gabbro is magnetite and in the shear zone monoclinic pyrrhotite.

Previous detailed studies of the orogenic gold deposits at Satulinmäki and Jokisivu have demonstrated that pyrrhotite is the main magnetic mineral in these formations, and is of hydrothermal origin. The AMS and NRM methods have been used to constrain the timing of the geological structures relative to gold forming processes. According to these results the injection of hydrothermal fluids took place during the syntectonic stage of the orogeny.

PD-PT-AU-RICH SULPHIDE ORES IN FOOTWALLS OF LAYERED MAFIC-ULTRAMAFIC IGNEOUS COMPLEXES

by

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Magmatic sulphide ore deposits in layered mafic-ultramafic igneous complexes are important sources of copper and nickel, and platinum group elements are additional valuable by-products. These deposits most commonly occur in the lower parts of layered complexes, along their footwall contacts. However, research and mineral exploration have recognised additional types of sulphide ores with high precious metal and copper contents in the footwalls of such large igneous bodies as the Sudbury Igneous Complex (SIC) and the Duluth Complex (DC). Exploitation of these footwall ores has already started in the Sudbury mining camp. The aim of the present summary is to review major characteristics of footwall ores under the SIC and DC in order to provide some ideas to evaluation of potential for this kind of ores in other areas.

FOOTWALL-TYPE ORES IN THE SUDBURY STRUCTURE

The location of the Sudbury Structure coincides with the boundary of the Superior (Archaean) and Southern (Proterozoic) provinces of the Canadian Shield, and its formation is related to meteorite impact event at about 1.85 Ga (Grieve 1994). Crystallization of the impact melt in the crater led to the formation of the approximately 30 km wide, 60 km long and 2–4 km thick SIC, which is characterised by large-scale layering with noritic units along the footwall contact, granophyre at the top and a transitional quartz-gabbro zone between them. Quartz-diorite dikes (offset dikes), which radially and concentrically intruded the footwall around the impact crater also comprise the SIC. The cover units of the SIC (Whitewater Group) accumulated in the crater and consist of breccia of the Onaping Formation at the bottom and shallow marine sedimentary units higher up in the sequence. The SIC is dominantly underlain by the Levack Gneiss Complex and the Cartier Batholith of the Archaean Superior Province in the North and East Ranges, whereas the footwall in the South Range is composed of Huronian metavolcanic and metasedimentary rocks, as well as Creighton and Murray granites of the Palaeoproterozoic Southern Province. The elliptical shape of the impact crater is the result of superimposed deformation related to the Mazatzal orogeny (1.6–1.7Ga).

Lenses of disseminated and massive contact-type Fe-Ni-Cu magmatic sulphide ores of the SIC most typically occur in local depressions along the basal contact between the norite and the basement rocks (Morrison 1994). Their host rocks are the discontinuous, noritic to quartz-dioritic Contact Sublayer, containing mafic-ultramafic inclusions, and the Footwall Breccia, consisting of mafic, ultramafic and felsic rock fragments in an igneous to metamorphic textured matrix of variable compositions In the Fe-Ni-Cu ores of the SIC, the Cu/Ni ratio is around 0.7 and the 'total precious metal' (TPM=Pt+Pd+Au) content is usually less than 1 ppm (Naldrett et al. 1994). Abundant pyrrhotite, pentlandite, chalcopyrite with some pyrite and magnetite characterise the mineral composition of these deposits.

The footwall ores of the Sudbury Structure occur in veins, disseminations and stockworks hosted by pseudotachylite breccia (Sudbury Breccia) bodies and fault zones. The Sudbury Breccia bodies are the results of the shock effect of the impact on the footwall units whereas the fault zones controlling distribution of ore may be related to the tectonic re-equilibrationof the impact structure. Veins and disseminations of the footwall ore are associated with the contact type ore bodies in some places (e.g. McCreedy West deposit) but also occur further away (up to 2 km) from the SIC/footwall contact, where there is no known physical connection to the contact ores (e.g. McCreedy East deposit, Broken Hammer property, Amy Lake zone). Farrow et al. (2005) classified footwall ores into `sharp-walled veins` and `low sulphide` groups according to their appearance and composition. The thickness of the 'sharp-walled veins' is up to 7 m and their orientations are most typically parallel/subparallel to the SIC/footwall contact. The occurrences of the `low sulphide` type ores are controlled by faults and fracture systems trending parallel and perpendicular to the contact zone. In the footwall ores, the Cu/Ni ratios are up to 7 and the total precious metal (TPM) concentrations are usually greater than 5–7 ppm; zones with concentrations of more than 30 ppm TPM and up to 27% Cu also occur. The veins consist of massive chalcopyrite with pentlandite, millerite, cubanite, bornite and magnetite as dominant minerals. Pt and Pd metals are mostly concentrated in bismuth-tellurides (e.g. michenerite, moncheite, froodite etc.), sperrylite and other antimony- and tin- bearing Pt-Pd minerals and gold. In the `low sulphide` ores, the total sulphide content is less than 5%, but the sulphide and precious metal mineralogy is similar to that in the `sharp walled veins`.

The Cu/Ni ratios in the `sharp-walled veins` usually increase as a function of distance from the contact and they are also poor in Ir, Os, Rh (Naldrett et al. 1994, 1999); therefore fractionation of sulphide melts during injection from the contact zone into dilatational structures of the footwall appears to be an important process in their formation. However, the `sharp-walled veins` also display hydrothermal alteration selvages with epidote, actinolite, biotite, stilpnomelane, ferropyrosmalite, quartz and carbonate minerals and Cl-enrichments in the host rocks also occur along these veins (Jago et al. 1994, Molnar et al. 2001, Hanley et al. 2003). On the other hand, the metal tenors in some of these veins deviate significantly from the most likely fractionation models (Péntek et al. 2008). These observations together with the results of fluid inclusion studies suggest that circulation of high temperature (>400°C) and very saline (30–60 NaCl equiv. wt%), as well as methane-enriched carbonic-aqueous fluids were also involved in formation of these veins (Li & Naldrett 1993, Molnar et al. 2001, Hanley et al. 2005, Péntek et al. 2008). LA ICPMS analyses of fluid inclusions from these kinds of ores have indeed found elevated copper and precious metal concentrations (Hanley et al. 2005)

The host rocks of the `low sulphide` class of footwall ores are characterised by intense hydrothermal alteration. Intergrowths of poikilitic epidote, Ni-enriched amphiboles, chlorite, quartz and carbonate minerals with Pt-Pd and sulphide minerals is a well-documented feature of these systems throughout much of the Sudbury structure (Péntek et al. 2008, Tuba et al. 2010). Fluid inclusion studies have also revealed an association of high-temperature (>300°C), high-salinity fluids with the stockworks and disseminations of `low sulphide` ore (Molnár & Watkinson 2001, Péntek et al. 2008).

MINERALIZATION IN THE GRANITOID FOOTWALL OF THE DULUTH COMPLEX

The Duluth Complex, which is a part of the ~1.1 Ga midcontinent rift system of North America, consists of more than twenty intrusions with mostly anorthositic and troctolitic compositions. Basaltic volcanic rocks of the North Shore Volcanic Group form the hanging-wall rock units of the DC whereas footwall units comprise the Archaean Giants Range batholith and the Ely greenstone belt, as well as the metasedimentary rocks (Virginia Formation) and banded iron formation (Biwabik Iron Formation) of the Early Proterozoic Animikie basin (Miller & Severson 2002). The sulphur rich sediments of the Animikie basin had an important role in the formation of the disseminated Cu-Ni-PGE sulphide mineralization along the basal contact of the DC (Ripley & Al-Jassar 1987, Thérieault 2000). Assimilation of sulphur from these footwall rocks into the intruding mafic magmas resulted in segregation of sulphide liquid, which formed the disseminated sulphide mineralization over a distance of approximately 60 km along the contact between the Archaean and Early Proterozoic footwall units and the Partridge River Intrusion and the South Kawishiwi Intrusion (SKI). These intrusions form the northwestern boundary of the DC.

The magmatic sulphide ore occurs in the lowermost, heterogeneous troctolite unit of the SKI as intercumulus disseminations. Inclusions and partial melts originating from the granitoid footwall contaminate this unit. The heterogeneous troctolite has a clearly discernible upper contact with either unmineralized homogeneous augite-troctolite or anorthositic-troctolite, especially where pegmatoids occur along the boundary. The ore in the heterogeneous troctolite has elevated Cu/Ni ratios (around 2.5–5) and consists of pyrrhotite, pentlandite, chalcopyrite, cubanite, talnakhite, ilmenite and magnetite. Peterson and Albers (2007) recognized two different types of metal distributions as a function of vertical distance from the contact. An increase in Cu and Ni contents (up to around 0.5–0.6% Cu and around 0.1% Ni) from the bottom to the top occurs where the mineralized unit is relatively thin (less than 150m). This kind of base metal distribution is usually associated with elevated TPM (>1 ppm, locally up to 5 ppm) concentrations. Increase of base metal tenors toward the lower contact with low (<1 ppm) TPM contents characterizes the thicker parts of the mineralized unit. These observations together with spatial variation of sulphur isotope data (Molnár et al. 2010) suggest that the SKI consists of multiple intrusions of mafic-ultramafic melts. The elevated Cu/Ni ratios and Pd>Pt concentrations of ore suggest early sulphide segregation with high silicate melt/sulphide melt ratios along the magma feeder channels, and further fractionation of sulphide droplets during transportation within crystal-melt mush during successive intrusive pulses.

The contacts of the mineralized lower unit of the SKI with the footwall granitoids have noritic compositions and fine grained, almost chilled character at many places. However, there are some zones where the contact is more gradational due to partial melting of the footwall granitoids. The thick (50–100m) partially melted contact zones in the footwall probably indicate the locations of magma channels in which multiple pulses of parent melts to the SKI have maintained high temperatures in the footwall for long periods of time. The intense recrystallization and partial melting textures in the host granitoids include replacement of amphiboles and biotite by fine grained masses of orthopyroxene, as well as development of decussate plagioclase textures and granophyric quartz-feldspar knots and patches around and between original rock-forming feldspars. The thick zones of partial melt in the footwall show irregular distributions of elevated Cu (>1%), while TPM concentrations > 1 ppm may be present up to 100 m from the contact. The mineralization in the footwall has disseminated and net-textured character, and the mineral assemblages of major sulphides (and Cu/Ni ratios) show a progressive change from pyrrhotite-pentlandite-chalcopyrite via chalcopyrite-cubanite-millerite to chalcopyrite-bornite(-pyrite) as a function of increasing distance from the contact. Results of model calculations suggest that the changes in Cu, Ni and precious metal composition in footwall mineralization can be related to fractionation of sulphide melts segregated from the parent magma of the SKI. The net-textured appearance of sulphide assemblages is consistent with infiltration of sulphide melt into partially melted zones of the footwall.

CONCLUSIONS

Examples presented in this review suggest that sulphide mineralization with high precious metal and copper contents may be common in the footwalls of large layered igneous complexes. These ores occur in the form of: a) massive sulphide veins with up to several meters thicknesses in brittle structures, b) disseminations in partially melted zones, and c) disseminations-stockworks in hydrothermal alteration zones.

The tonnages of known footwall ores are not particularly large (up to several Mt) in comparison to the disseminated or massive magmatic sulphide orebodies within mafic-ultramafic complexes. However, they may still be economic due to their high precious metal and copper contents; deposits in the Sudbury Structure exemplify this.

In Finland, the characteristics of the Kilvenjärvi Cu-(Ni)-PGE deposit and similar occurrences beneath the Narkaus Intrusion (Iljina 1994, Andersen & Thalhammer 2006) are comparable with the footwall ores of the SIC and DC. Considering the widespread distribution of large layered mafic-ultramafic intrusions in northern Finland, further recognition of footwall ores may be expected in areas where the basal parts of the intrusions are mineralized and thick zones of partially melted footwall rocks are present. Fault systems along the contacts may also be favourable locations for footwall ores of magmatic-hydrothermal origin.

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3D MODEL OF THE KITTILÄ BLOCK AND USING IT AS A TOOL FOR ESTIMATING THE GOLD POTENTIAL OF THE AREA

by

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INTRODUCTION

The Paleoproterozoic Central Lapland Greenstone belt (CLGB) is one of the largest greenstone belts in the world, extending ca. 450 km from Norway in the northwest to Russian Karelia in southeast (Fig.1). The CLGB consists of a rift-related volcanic-sedimentary succession deposited on Archean basin during multiple rift stages between 2.44 and 2.0 Ga. The core of the CLGB consists predominantly of tholeiitic volcanic rocks of the Kittilä Group, which has been proposed to represent an allochthonous or para-autocthonous terrane within the CLGB (e.g. Hanski 1998, Lahtinen et al. 2005). This unit, which is referred to in this work as Kittilä block, is bound by tectonic contacts along its eastern, southern, and western margins. The Kittilä block is an area of significant economic interesting area as numerous orogenic gold deposits and occurrences are known within the unit and along the Sirkka thrust zone (STZ), which delimits the southern margin of the block.

The GTK initiated the CLGB 3D modelling project in 2008 in order to evaluate and develop methods for creating 3D geological models at local and regional scale. This study presents results of the regional scale geological modelling of the Kittilä block and adjacent areas. Implications of the results for the tectonic evolution of the area as well as gold potential are also discussed. The 3D model is based on various data sets of the area including seismic data (FIRE & HIRE), gravity data, audiomagnetotelluric (AMT) data, aerogeophysical data and their derivatives as well as geological mapping data.

GEOLOGY OF THE KITTILÄ BLOCK AND ADJACENT AREAS

The Kittilä block forms an irregular shaped area extending about 80 km in an E–W direction and 55 km in a N–S direction, representing one of the largest accumulations of mafic metavolcanic rocks within the Fennoscandian Shield. The Kittilä block consists dominantly of tholeiitic metavolcanic rocks with minor interbeds of metagraywackes, phyllites, graphite- and sulfide-bearing schists and tuffites, carbonate rocks, and banded iron formations (Lehtonen et al. 1995). The bedrock immediately surrounding the Kittilä block consists mainly of rift-related volcanic-sedimentary sequences of the Savukoski Group as well as reworked Archean basement. In the west the Kittilä block is bordered by or overlain by 1.89–1.86 Ga syn-orogenic intrusions and clastic Svecofennian sedimentary rocks.

The bedrock of the area was metamorphosed and repeatedly deformed during the 1.91–1.80 Ga Svecofennian orogenic events. The most prominent structural features were generated during the D_2 stage between 1.91 and 1.86 Ga which was related to simultaneous or successive thrusting events from NE and S (e.g. Ward et al. 1989, Hölttä et al. 2007). The last ductile deformation stage (D_3) took place between 1.86–1.80 Ga. The kinematic indications of this stage vary considerably within the area and it is unclear whether the D_3-stage consists of several localized sub-stages (e.g. Hölttä et al. 2007, Patison 2007). The peak metamorphic conditions in the area were reached during the D_2-stage. A characteristic feature of the Kittilä block is that the metamorphic assemblages indicate lower metamorphic grade (mid-greenschist facies) than in the surrounding areas (Hölttä et al. 2007).

The most important structures bounding the Kittilä block are the south dipping STZ in the south and the west dipping Jerisjärvi thrust zone (JTZ) that forms part of the Kolari–Pajala shear zone system in the west. Several major NE- to N-

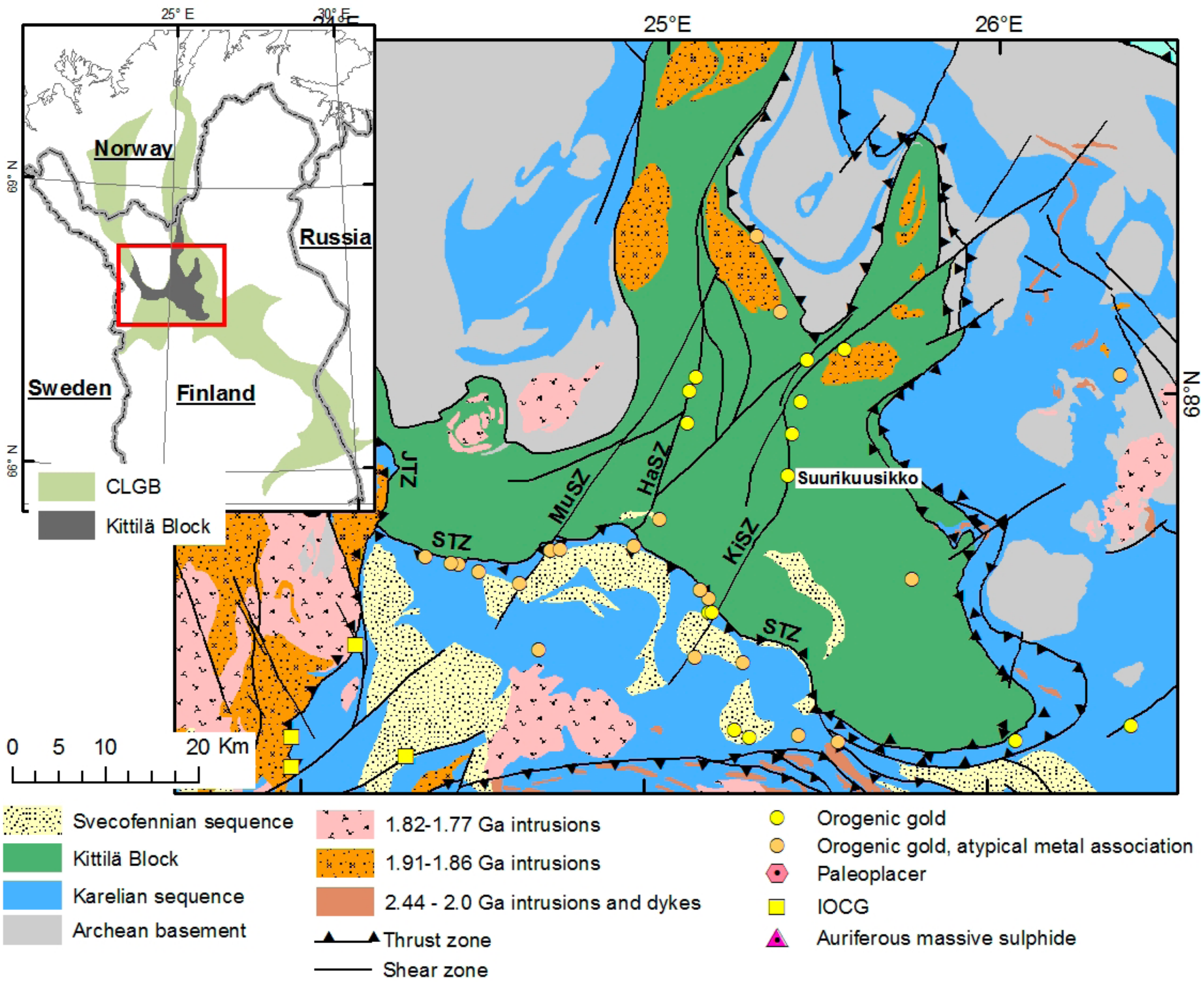

Fig. 1. Geological map of the study area with location of the known gold deposits. MuSZ = Muusa shear zone, HaSZ = Hanhimaa shear zone, KiSZ = Kiistala shear zone, STZ = Sirkka thrust zone, JTZ = Jerisjärvi thrust zone. Modified after Bedrock of Finland – DigiKP.

striking strike slip shear zones have been outlined within the Kittilä block. These are (from east to west) Muusa, Hanhimaa, and Kiistala shear zones (MuSZ, HaSZ, and KiSZ, respectively). Outcrop and drilling data across the KiSZ and HaSZ indicate dextral horizontal movement (Patison 2007). The MuSZ is not seen in outcrop, but based on geophysical maps it has an apparent sinistral component. The known orogenic gold deposits are focussed along the STZ and the HaSZ, and KiSZ, the last of which hosts the 6 Moz Suurikuusikko deposit.

MODELLING RESULTS

The modelling results indicate considerable thickness variation within the Kittilä block (Fig. 2), the thickest part being somewhat greater than 9 km, within the central part of the block. However, the average thickness of the Kittilä block within the modeled area is about 3.5 km. The block becomes considerably thinner to the west and the "base" of the block reaches the present erosion level in the SE part.

DISCUSSION

The 3D model of the Kittilä block indicates that it is considerably thicker than suggested by previous geophysical 2D models (ca. 6 km, Lehtonen et al. 1998). The thickness variation is dramatic and it is unlikely to be primary in character, considering the geological history, rather being a result of tectonic thickening via

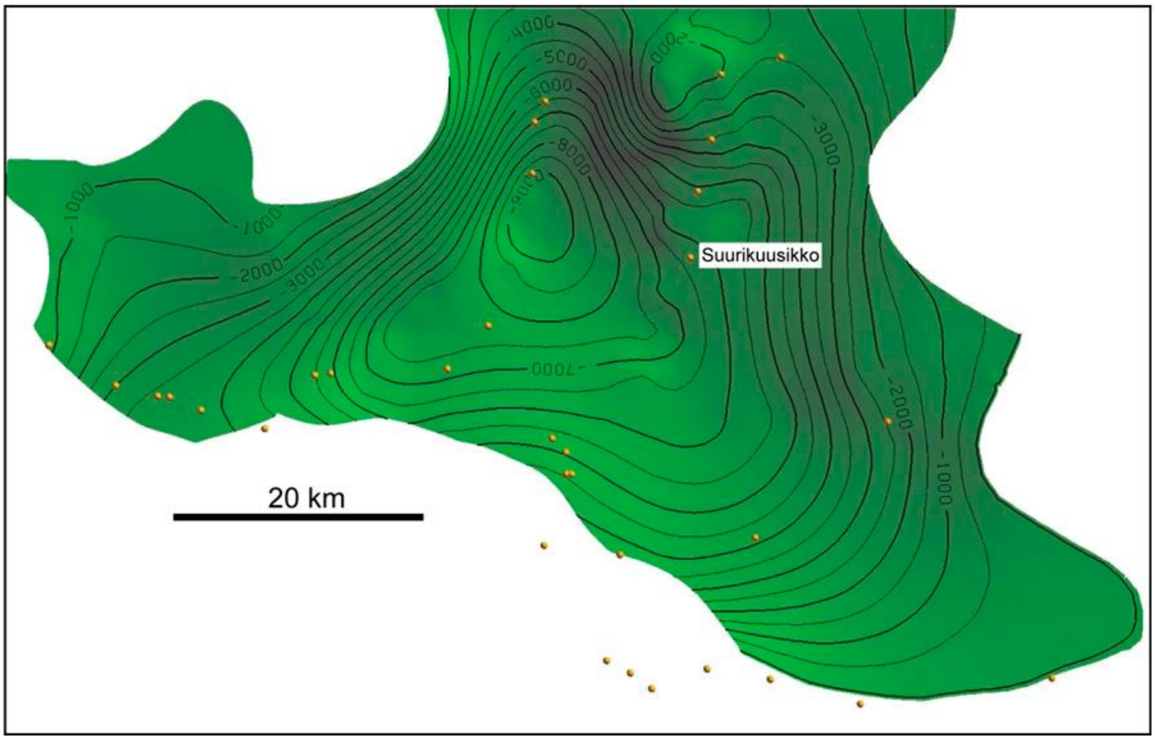

Fig. 2. Depth contours (in meters) of the base of the Kittilä block (green) and location of known gold deposits (yellow dots).

folding and/or stacking of the rocks during Svecofennian orogenic events; the current 9 km maximum thickness of the Kittilä block is nearly double that of average modern oceanic crust (5 km). . Based on visual estimation it is conceivable that the 3D shape of Kittilä block was created via compression from NE and S, however, further numerical paleostress modelling would be useful before any conclusive statements can be made. The thickness variation is not reflected on the metamorphic maps as most of the modeled area is mapped as mid-greenschist facies zone in metamorphic maps (Hölttä et al. 2007).

The modeled Kittilä block allows us to make rough estimations on the gold potential of the region. Groves et al. (1998) presented a genetic model for the orogenic gold deposits in which the metals and fluids involved are released from the country rocks during the metamorphism (with or without input from intrusions) and are focused into suitable structures which act as pathways, and further deposited into suitable traps. The data from Otago and Alpine schists in New Zealand show a clear pattern of depletion in gold and gold-related metals from rocks undergoing progressive metamorphism (Pitcairn et al. 2006). Their work indicates that gold concentrations in sedimentary and mafic volcanic rocks metamorphosed in amphibolite facies conditions show 50–80% depletion compared with their unmetamorphosed varieties, which is in agreement with the model presented by Groves et al. (1998).

Applying the model by Groves et al. (1998) to the Kittilä area we develop a scenario in which the mafic volcanic rocks are the dominant source for the fluids and gold, and these are released from the rocks in metamorphic reactions involving devolatization via breakdown of hydrous silicates. In mafic rocks the devolatization is generally strongest around the greenschist-amphibolite facies boundary at around temperatures 525°C. Because there is no precise pressure estimate for peak metamorphic conditions from the Kittilä block, we use a temperature gradient of 25°C/km, which is an average gradient for Barrovian-type metamorphism. Using this gradient, and 375°C for the current Kittilä block surface, the 525°C greenschist-amphibolite facies transition boundary is at 6 km depth. The data from the literature suggest that average background gold concentrations for mafic volcanic rocks vary between 0.75 ppb and 4.7 ppb depending on the type of the mafic volcanic rocks (Pitcairn 2012 and references therein). As data for average background gold concentrations are lacking from the Kittilä metavolcanic rocks, we perform our calculations using both 1 ppb and 3 ppb Au concentrations. A density of 2950 kg/m^3 is used in calculating the mass. Using the values above and the volume outlined by our 3D model, the total mass of Kittilä block rocks which have undergone amphibolite facies metamorphism is 2245 billion tonnes and the amount of gold it contained using 3 ppb and 1 ppb average grades is ca. 6700 t (217 Moz) and 2250 t (73 Moz), respectively. These figures are considerable compared with the currently known gold resources within the Kittilä block (~6 Moz). Obviously, the gold and fluids released in depth by metamorphism need to be focused into a suitable structure like the KiSZ.

We are aware of the numerous assumptions and hypothetical nature of the calculations presented above, however, we believe that they do give some idea of the gold potential of the Kittilä block. Obviously, until better estimates on the temperature gradient and the true background gold concentrations are available for refining the calculations, the above presented figures should be considered as "Blue Sky" estimates. Nevertheless, the work presented shows the power of 3D modelling and a potential application for regional-scale geological 3D models.

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3D MODELLING of the Kolari district supracrustal units – implications FOR the stratigraphy and mineral potential of the region

by

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INTRODUCTION

The Kolari district is located in northern Finland adjacent to the Finnish–Swedish border. The area has been under active exploration by various companies for decades and as a result about 15 iron ± Cu-Au deposits have been discovered. Various genetic interpretations have been proposed for the known deposits, including metamorphosed syngenetic iron formations (e.g. Mäkelä & Tammeinmaa 1978, Väänänen 1998), strata-bound, intrusion- related epigenetic skarn deposits (Hiltunen 1982) or epigenetic Iron oxide-Cu-Au deposits (Niiranen et al. 2007). In 2010, GTK in co-operation with Northland Resources S.A., a company which is currently carrying out exploration and development of the Kolari deposits, ran a deep seismic profile program (HIRE) over key targets areas in the Kolari district. The data became available for research after a one year quarantine period and was used at GTK in the Central Lapland 3D modelling project. This study presents preliminary results of the 3D modelling done using the Kolari HIRE data.

GENERAL GEOLOGY OF THE KOLARI AREA

The supracrustal rocks of the Kolari region consist of Karelian rift sequence tholeiitic volcanic rocks and associated sedimentary rocks, overlain by Svecofennian molasse-type clastic sedimentary rocks. Voluminous 1.89–1.86 Ga Haparanda Suite calc-alkaline monzonite and diorite intrusions and 1.82–1.79 Ga granitoids comprise the intrusive rocks of the area (Hiltunen 1982, Väänänen 1998, Niiranen et al. 2007). Minor amounts of 2.2–2.0 Ga dolerite dykes have been recognized in the southern part of the district. The rocks were subjected to multiphase deformation and metamorphism during the 1.91–1.80 Ga Svecofennian orogenic events. The main deformation features were generated during the D_2-stage at 1.89–1.86 Ga during which amphibolite facies peak metamorphic conditions were reached (e.g. Hiltunen 1982, Niiranen et al. 1997). The tectonic features of the Kolari area are dominated by juxtaposing and braided NE- to N- striking shear and thrust zones that form part of the major Baltic-Bothnian shear zone system which has been suggested to represent the boundary between the Norrbotten craton in the west and the Karelian craton in the east (Berthelsen & Marker 1986, Lahtinen et al. 2005).

STRATIGRAPHY

The lowermost supracrustal rocks of the study area comprise the Niesakero Formation quartzites and mica schists of the >2.2 Ga Sodankylä Group (Fig. 1). These are overlain by the 2.2–2.0 Ga Savukoski Group which, in the Kolari region, has been divided into the Kolari Formation and Rautuvaara Formation. Both of these formations consist of tholeiitic volcanic rocks, graphitic phyllites, quartzofeldspathic schists and marbles. The Rautuvaara Fm is separated from the Kolari Fm based on the fact that the former includes various skarns and skarn-hosted iron occurrences (Hiltunen 1982, Väänänen 1998). The Tapojoki Fm quartzites and mica schists, Juurakkojärvi Fm mica schists, Tuulijoki Fm felsic volcanic rocks, and the Ylläs Fm quartzites and conglomerates represent the youngest stratigraphical units in the area and belong to the <1.89 Ga Kumpu Group.

MODELLING RESULTS

The seismic survey data show three gently dipping to subhorizontal, highly reflective units which can be traced through several of the HIRE profiles. The uppermost highly reflective units coincide with the mafic tholeiitic rocks of the Rautuvaara Fm in the Hannukainen and Kuervitikko area. This unit hosts the bulk of skarns and ores in the area. At Hannukainen, drilling penetrated this lithology as well as the underlying mica gneiss and quartzite units, which both correlate with similar rocks in the the Niesakero Fm, outcropping east of Hannukainen (Hiltunen 1982). The second highly reflective unit is also assumed to represent this unit but the lowermost reflector set cannot be directly correlated to any outcropping unit within the study area. Based on the HIRE data as well as airborne geophysics the three highly reflective units were modeled as stratigraphical units in 3D using Gocad software. Modeled units form a folded, gently SW dipping package. The package has a form of a NE opening open fold with a fold axis plunging ca. 25 degrees to SW. This orientation coincides with the dominant stretching lineation in the Kolari district (e.g. Hiltunen 1982, Niiranen et al. 2007). Interestingly, the lithology mapped as Rautuvaara Fm rocks in Rautuvaara area cannot be linked to the same highly reflective unit that hosts the Hannukainen and Kuervitikko ores. Instead, it appears that the top of the modeled uppermost unit is at a depth of about 2.5 km in the Rautuvaara area and thus the current stratigraphical interpretation is wrong with respect to the Rautuvaara Fm.

Another feature that was clearly visible in the seismic data was the NE striking Äkäsjoki shear zone. This could be traced in several profiles as a transparent zone cross cutting the reflectors down to at least 3 km depth. The data indicate that the Äkäsjoki shear zone dips about 80 degrees to NW, and appears to be developed parallel to the axial plane of the above described open fold structure.

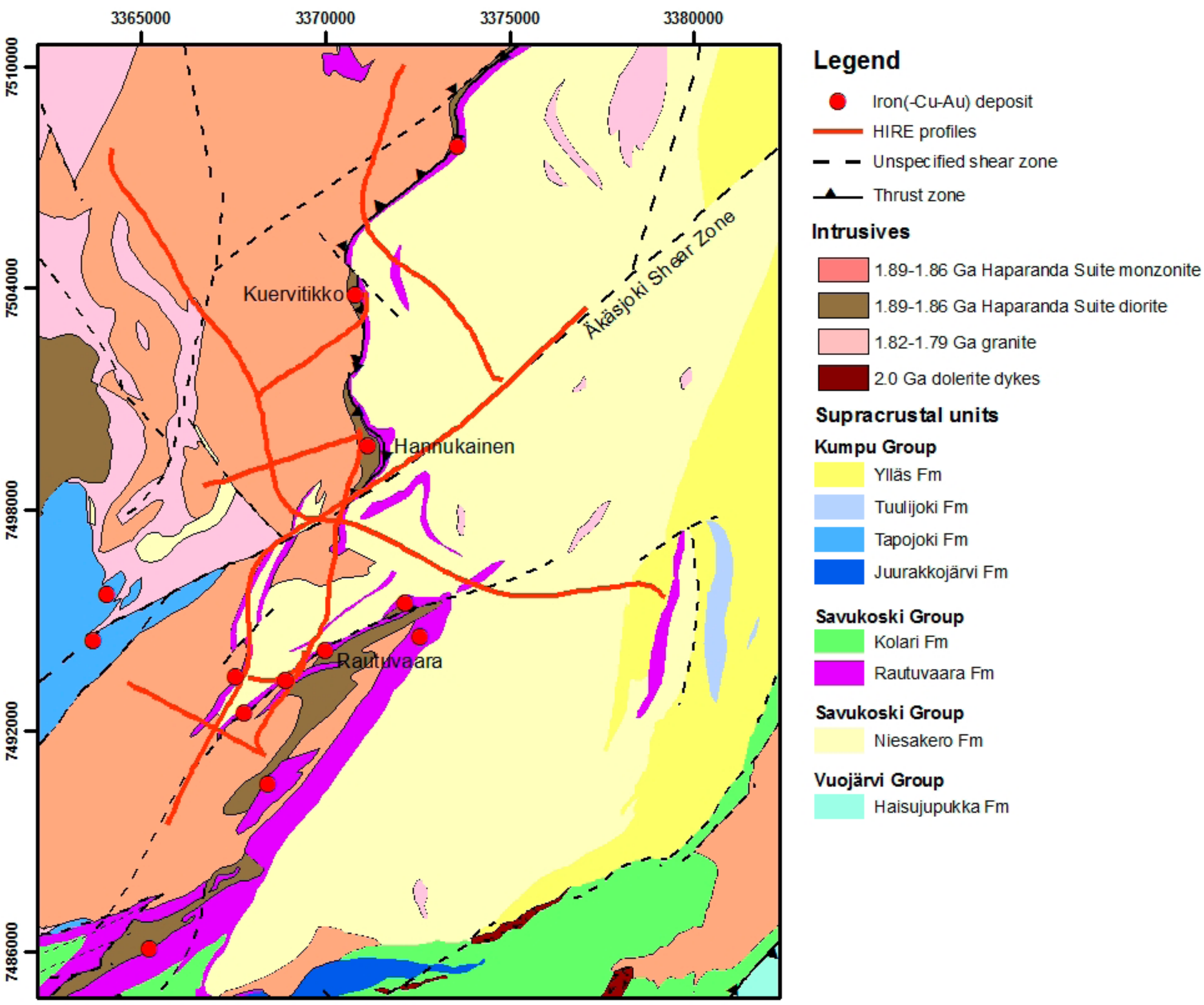

Fig. 1. Bedrock map of the study area with locations of HIRE seismic profiles and known iron-Cu-Au deposits. Modified after Bedrock of Finland – DigiKP.

DISCUSSION AND CONCLUSIONS

The HIRE data indicate that it is impossible for that the same stratigraphical unit to host all the iron ± Cu-Au deposits in the district, and that the current stratigraphical interpretation requires revision. Although there is some justification in geophysical maps for the current interpretation, and the lithologies are broadly similar between the Rautuvaara and Hannukainen areas it appears that when the Rautuvaara Fm was defined, there was too much emphasis on the hypothesis that the ores and the ore-hosting skarns are strata-bound, such that the distribution of the formation has been extrapolated to include all areas where skarns are present. Since there is no clear justification for dividing the Savukoski Group rocks into two formations (Kolari and Rautuvaara) in the Kolari region, we suggest that they should be merged into one formation. The seismic data indicate that this formation has a minimum thickness of about 1800 meters (true thickness). The results of this study also direct implication for exploration models for the Kolari-type deposits: the focus should not be on a particular stratigraphical unit but broaden the potential areas to other rock types, too.

The results presented here demonstrate the need to incorporate 3D analysis in geological interpretations. There is clearly a need to test the current 2D interpretations using 3D visualization. The seismic data at Kolari enabled us to carry out relatively robust interpretation. However, the 2D interpretations can also be tested also using semi-synthetic models with data limited to geophysical maps and structural observations from both outcrops and drill core.

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MODELING THE STRUCTURAL EVOLUTION OF THE BEDROCK IN FINLAND AT 1:1 MILLION SCALE

by

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The evolution of the bedrock in Finland has been previously modeled in several studies, more recently e.g. by Lahtinen et al. (2005) as part of their plate tectonic reconstruction covering the entire Fennoscandian Shield. The tectonic boundaries separating or splitting crustal units in the model of Lahtinen et al. (2005) may be considered ore potential zones because of the large amounts of fluids that could have been channeled along these boundaries. Convergent boundaries may represent different stages of orogeny (terrane accretion, arc-continent accretion, or intracratonic boundaries caused by continental collision). Generally the original convergent boundaries have been modified by deformation during subsequent stages of orogeny and post-orogenic isostatic readjustments. Overprinting of the initial boundaries by later events means that these features now constitute structurally complex zones (e.g. thrusts and strike-slip shear zones overprinted by extensional shear zones and normal faults). In addition to lateral displacements the boundaries have been subjected to vertical displacements: the boundary at the present erosion surface may therefore be in a different position than the same boundary at 10–20 km depth.

Representation of tectonic features at a scale of 1:1 million, as in the on-going GTK 1:1 million map project, requires more detailed tectonic modelling than that in Lahtinen et al. (2005). An essential part of this modeling is recognizing that the crust consists of rigid units separated by zones of weaker (sedimentary or volcanic-sedimentary) material in which most of the orogenic strain is concentrated. We can assume that during the break-up of the Archean Karelian continent, which culminated in the development of a divergent margin at c. 2.05 Ga, blocks of the Archean crust probably were dismembered and drifted away from the attenuated continent. These blocks may have remained fairly close to or within the bounds of the passive margin. After conversion of the passive margin into an active convergent margin the Svecofennian orogeny commenced with an accretionary stage at 1.91 Ga. The rigid bodies that were accreted to the Archean craton were arc complexes, possibly comprising older Proterozoic microplates (nuclei) and attached volcanic arcs. These dominantly rather juvenile bodies were warm and therefore deformed in a ductile manner (including folding). Their docking to the passive margin eventually caused accretion of the outboard Archean blocks to the more proximal parts of the thinned craton margin. These older crustal blocks were presumably colder and more rigid than the recently accreted ones. The lateral displacement and rotation of such rigid blocks at the Archean cratonic margin controlled deformation in northern Finland: deformation in the rigid blocks was partitioned into shear zones whereas supracrustal rocks squeezed between these blocks were deformed mainly by folding. Continental collision at 1.84–1.80 Ga further south (Lahtinen et al. 2005) caused intracontinental low-angle thrusting in southern Finland, and subsequent orogenic collapse and isostatic readjustments at 1.79–1.77 Ga led to the present structural pattern, with crustal blocks representing different exhumation levels.

Modeling of the tectonic evolution at a scale of 1:1 million has been initiated from northern Finland. In addition to the existing knowledge of lithology and structures, previous evolutionary models, interpretation of the reflection seismic FIRE4 profile (Patison et al. 2006) as well as variation in metamorphic grade have been taken into account. Central Lapland, which has a high potential of gold and base metals, is a challenging area because of its structural complexity. The area has been divided into subareas, and structural evolution including bulk shortening/extension directions for deformation stages, has been interpreted for each of these subareas. A structural evolution model for central Lapland has been outlined by combining interpretations of the subareas. A similar method will be used for the rest of Finland.

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FUZZY LOGIC DATA INTEGRATION TECHNIQUE USED AS A NICKEL EXPLORATION TOOL

by

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Prospectivity analysis can be performed in GIS using various techniques. There are two main approaches, (1) Empirical (supervised, data driven) and (2) Conceptual (un-supervised, knowledge driven) (Bonham-Carter 1994, Carranza 2008). The first approach is suitable for mature, brownfields exploration terrain, in which there is an abundance of known mineral deposit sites for 'training' the models. Alternatively, in greenfields exploration, with only a limited number of adequate training sites, the conceptual approach enables the use of different expert-defined exploration criteria.

This paper demonstrates the use of fuzzy logic data integration in GIS to conduct prospectivity analysis for magmatic nickel deposits. The example used to demonstrate the power of this GIS tool is from the Palaeoproterozoic Central Lapland Greenstone Belt, Northern Fennoscandian Shield, Finland. The analysis was performed using the publicly available SDM (Spatial Data Modeller) code (Sawatzky et al. 2009) for the ArcGIS 9.3.1 GIS platform.

Within the study area, two magmatic nickel deposits are already known and there is currently considerable nickel exploration activity. Due to the lack of sufficient training data for supervised techniques, the knowledge-driven fuzzy logic technique was used for the prospectivity analysis. We integrate spatially referenced high-resolution airborne geophysical and regional scale geochemical and gravity data sets based on a simple and rational exploration model to define areas favourable for this deposit type (Fig.1). Magmatic nickel deposits are related to rock types that are typically characterized by local magnetic and gravity anomalies. These deposits can also be the source of anomalies of nickel, copper and cobalt within the overlying glacial till. These straightforward exploration criteria were translated into a fuzzy logic model in GIS.

To test the quality of the model and to optimize the performance of a prospectivity model we can use various statistical methods. In this paper the model optimization and validation was done by using the receiver operating characteristics (ROC) technique (Fawcett 2006) to describe the trade-off between hit rates and false alarm rates of models. Due to the lack of known nickel deposits, we used the current exploration license areas as the true positive cases and a set of random locations within the same area of interest as the true negative cases. This validation example indicates that the exploration criterion of the current exploration

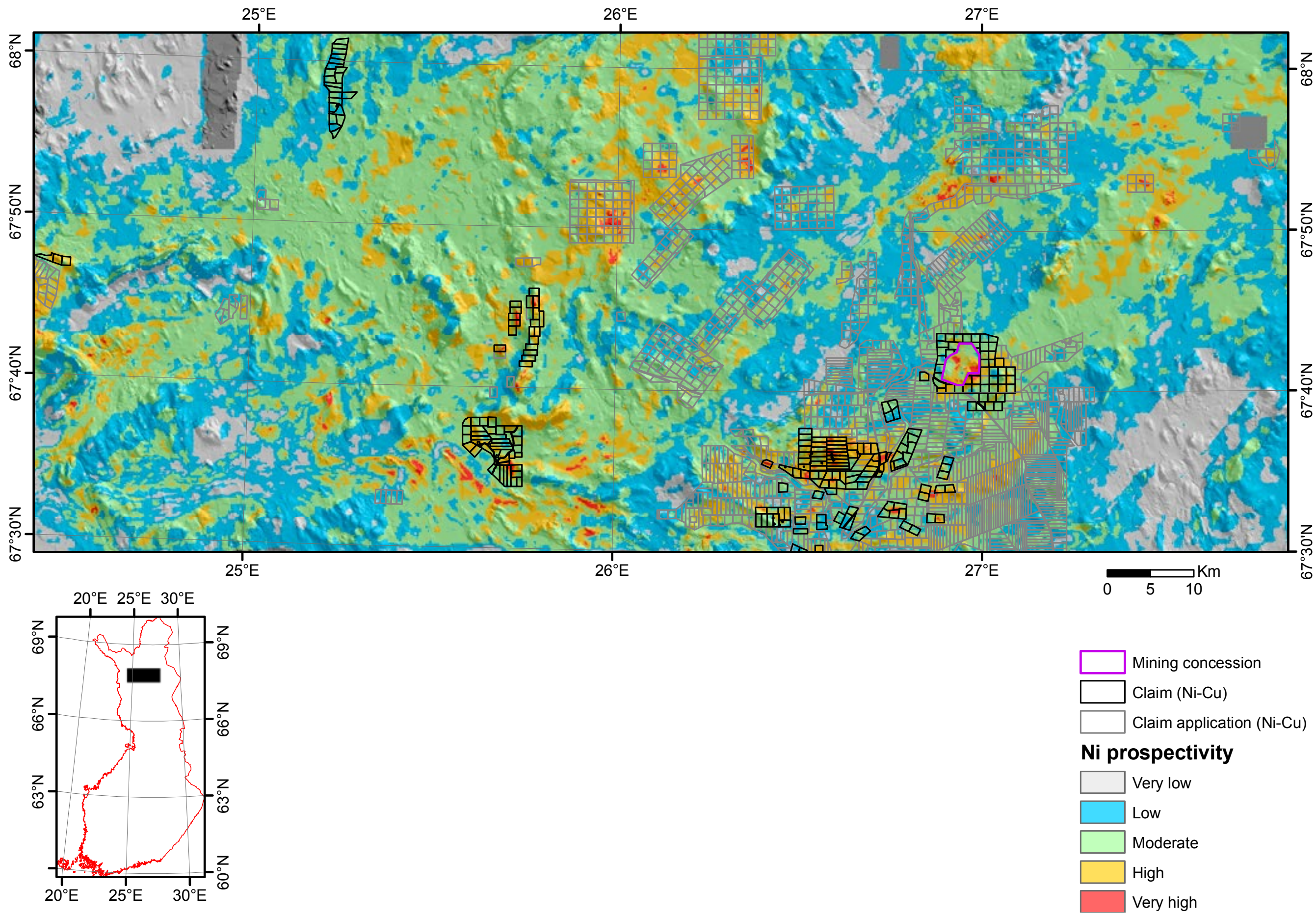

Fig. 1. Ni-prospectivity map, Central Lapland, Northern Fennoscandian Shield.

license holders may be somewhat similar to the exploration model described in this paper. Furthermore, we can clearly show that the ROC technique provides a robust model validation and optimization technique, providing that suitable validation data exist.

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GOLD PROSPECTIVITY OF JUNIPER AND SPRUCE IN SUURIKUUSIKKO SHEAR ZONE

by

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Exploration in glaciated terrains, such as northern part of Fennoscandian Shied, is commonly hampered by the presence of dispersed glacial and post-glacial sediments. Biogeochemistry – chemical analysis of soil organic matter and plant species – has been extensively used for detecting buried mineralization in Canada and Russia. In Finland, only a few plant species have been investigated for this purpose (Pulkkinen et al. 1989). The basis of biogeochemical prospecting relies on the fact that plant roots penetrate soil horizons, have access to weathered/fractured bedrock and the associated local groundwater and effectively uptake elements. Therefore, plants containing anomalous concentrations of certain elements can be used as indicators of mineralization. In trees, metals exceeding metabolic needs are transported to extremities such as bark, leaves, and twigs.

The study sites are located in the Central Lapland Greenstone Belt, within the municipality of Kittilä,. The main bedrock structure is the NE–SW trending Suurikuusikko shear zone and the subparallel Suasselkä postglacial fault. The sampling transects, 120 sites for Norway spruce (*Picea abies*) and 82 sites for common juniper (*Juniperus communis*), were oriented transversely with respect to the Suurikuusikko shear zone and the Suasselkä postglacial fault. Along the transects glacial till and juniper/spruce twigs were sampled and 57 spring water samples were collected. Mineral soil samples were digested with aqua regia and twig samples with nitric acid. Element concentrations were determined with ICP-AES and ICP-MS. To analyze concentrations of Au, soil and twigs samples were digested with aqua regia, Au was preconcentrated with mercury and concentrations then determined with GFAAS. Concentrations of As in spring water samples were determined with ICP-MS.

We found no correlation between soil and twig Au concentrations, indicating that a high proportion of the element uptake derives from the bedrock and/or groundwater associated with neotectonic fractures, rather than glacially dispersed soil. Furthermore, spatially discrete high values of soil Au indicated the presence of the nugget effect. The concentrations of Au in Norway spruce were as low as 0.53±0.79 μg kg^{-1}, thus indicating that in this case spruce twigs were insufficient for Au exploration, whereas common juniper accumulated Au up to 54 μg kg^{-1}. According to the Mann-Whitney test, Au concentrations of juniper twigs were significantly ($p<0.001$) different between the sites ≤30 m distance from the Suasselkä postglacial fault (14.5±10.2 μg kg^{-1}, *n*=14) and the other sites (5.7±8.8 μg kg^{-1}, *n*=68), whereas Norway spruce and glacially dispersed soil gave no indication of the possible mineralization. The bedrock within the Suasselkä postglacial fault is highly fractured and we speculate that the groundwater flow in the bedrock is relatively unimpeded, a conclusion which is also supported by the exceptionally large number of springs. In addition to Au, As concentrations in juniper were also high within part of the Suasselkä fault zone. Low soil As concentrations and nearby As-rich (30–39 μg l^{-1}) springs indicate that the juniper Au-As anomaly was generated through groundwater flow in fractured arsenopyrite-bearing (Härkönen et al. 2000) bedrock, followed by uptake within the root system. With the common association between Au and As, the results suggest that the analysis of Au and As concentrations in common juniper is a potential biogeochemical exploration method for Au.

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UNDISCOVERED OROGENIC GOLD RESOURCES IN NORTHERN FINLAND

by

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INTRODUCTION

The undiscovered resources of important metals in the Finnish bedrock are being systematically assessed by Geological Survey of Finland using the three-part quantitative mineral resource assessment method (Singer 1993, Singer & Menzie 2010). This includes the selection or formulation of deposit models for the relevant ore deposit types, the delineation of areas where geology permits the existence of such deposit types (permissive tracts), the estimation of the number of undiscovered deposits within the permissive tracts, and the calculation of metal tonnages for the undiscovered deposits at various levels of probability.

We describe here the results of the three-part quantitative assessment of orogenic gold resources down to a depth of one kilometre in the bedrock in the northern part of Finland, north of the Central Lapland Granitoid Complex (Fig. 1).

GOLD DEPOSITS IN NORTHERN FINLAND

The known gold deposits and occurrences in northern Finland mostly belong to the orogenic gold deposit type (Eilu et al. 2007, Eilu & Pankka 2009). Most of the potentially existing, yet undiscovered gold resources in the area are inferred to belong to the orogenic type. Two orogenic gold deposits in the area were considered to be sufficiently well known for inclusion within the grade-tonnage model (Fig. 1). Together these two deposits, Suurikuusikko and Saattopora, contain 249 t of gold (Eilu & Pankka 2009, Agnico-Eagle Mines Ltd 2012a, 2012b). In addition to the well-known deposits, at least 38 partially explored orogenic-type gold occurrences have been identified (Eilu & Pankka 2009) and at least six partially explored iron oxide-copper-gold (IOCG) deposits, two partially explored palaeoplacer occurrences and five partially explored occurrences of uncertain type are known in the area (Eilu & Pankka 2009, FODD 2010). The importance of these other deposit types for the total gold endowment in northern Finland was considered minor, and they were not included in the assessment.

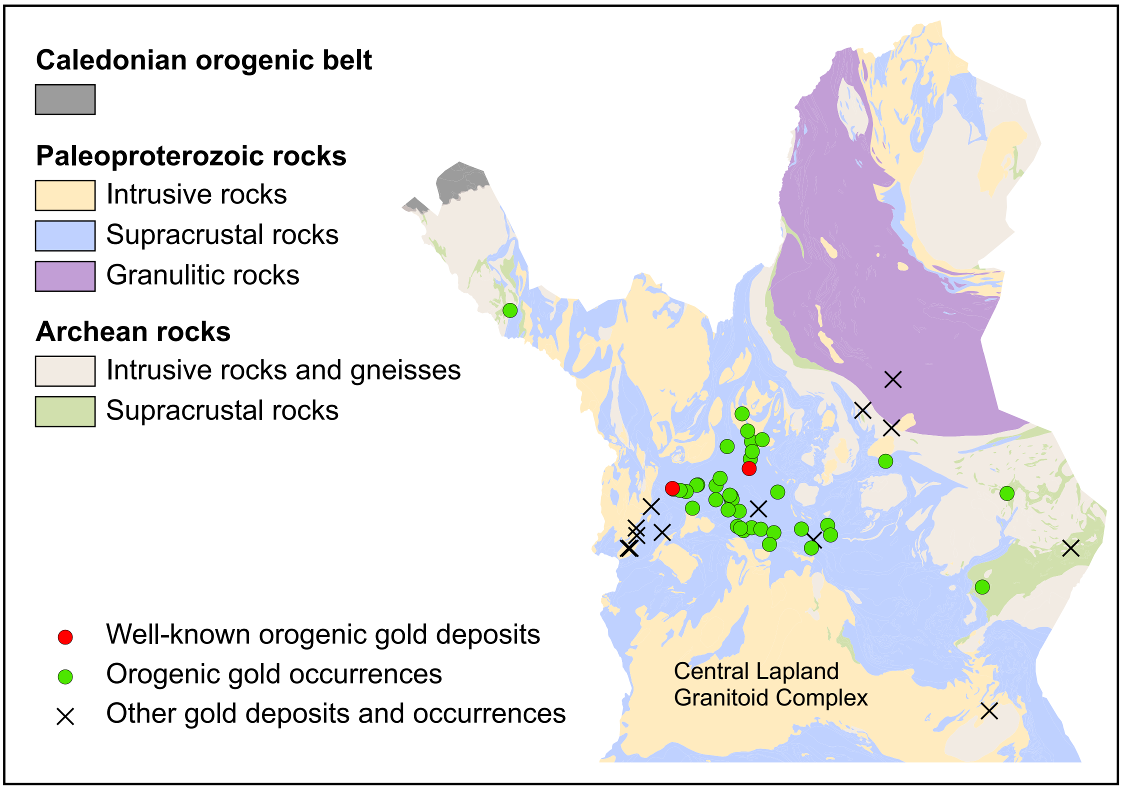

Fig. 1. Generalised geology of the study area in northern Finland. Simplified from Bedrock of Finland – DigiKP. Gold deposit data from Eilu & Pankka (2009) and FODD (2010).

DEPOSIT MODELS

A descriptive model was created based on literature on orogenic gold deposits and characteristics of deposits in Finland. A grade-tonnage model was constructed using publicly available data on 73 well-known, fully delineated orogenic gold deposits from Finland (15), Sweden (6) and Australia (52). Most of the known orogenic gold deposits and occurrences in Finland were considered to be inadequately delineated and were thus excluded from the grade-tonnage model. Five of the Finnish deposits in the model are Archaean; all the other deposits are Proterozoic in age. There are no statistically significant differences in either total ore tonnage or average gold grade between countries. The Finnish Archaean deposits have a lower median ore tonnage (0.59 Mt) compared to all the Proterozoic deposits in the model (2.1 Mt). The difference between the two groups is statistically marginally significant at the 5% probability level. However, since there are only five Archaean deposits in our data set, no separate grade-tonnage model was created for Archaean orogenic deposits.

The ore tonnages and average gold grades in the grade-tonnage model do not differ from a lognormal distribution at a statistically significant level (Fig. 2). The median tonnage of the model is 1.9 Mt and the median gold grade is 2.6 g/t Au.

PERMISSIVE TRACTS

Altogether 11 permissive tracts were delineated for orogenic gold deposits in the area (Fig. 3). The tracts are controlled by the lithology and metamorphic grade

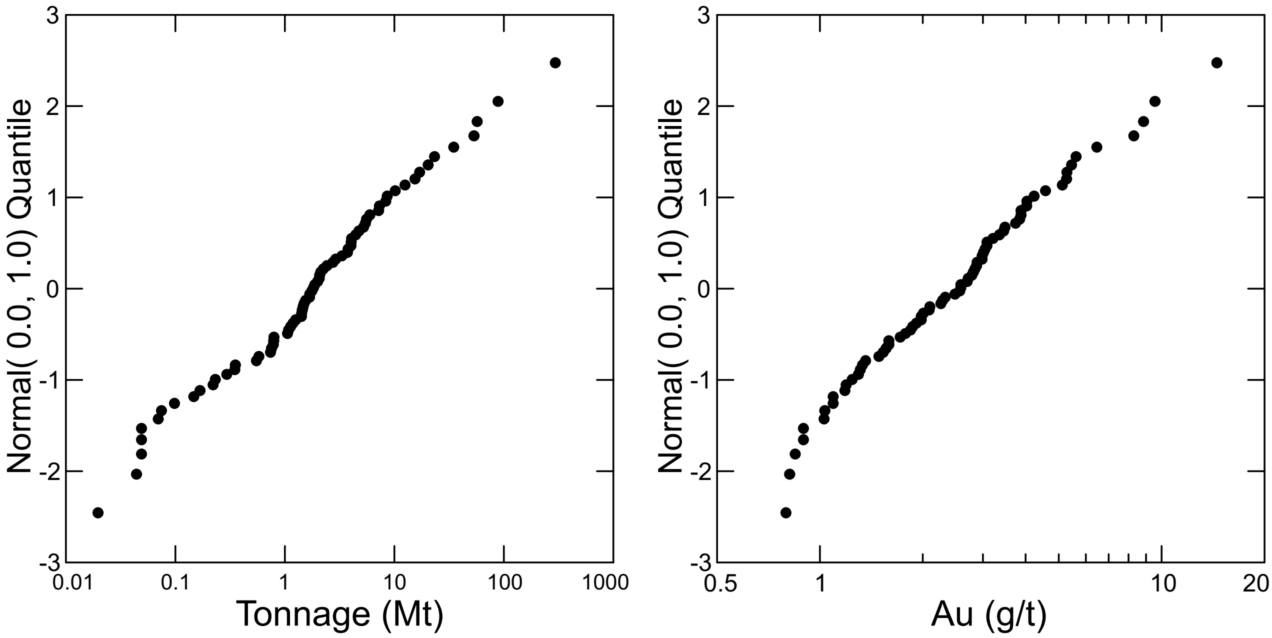

Fig. 2. Normal probability plots for logarithmic values of total ore tonnage and average gold grade of orogenic gold deposits in the grade-tonnage model.

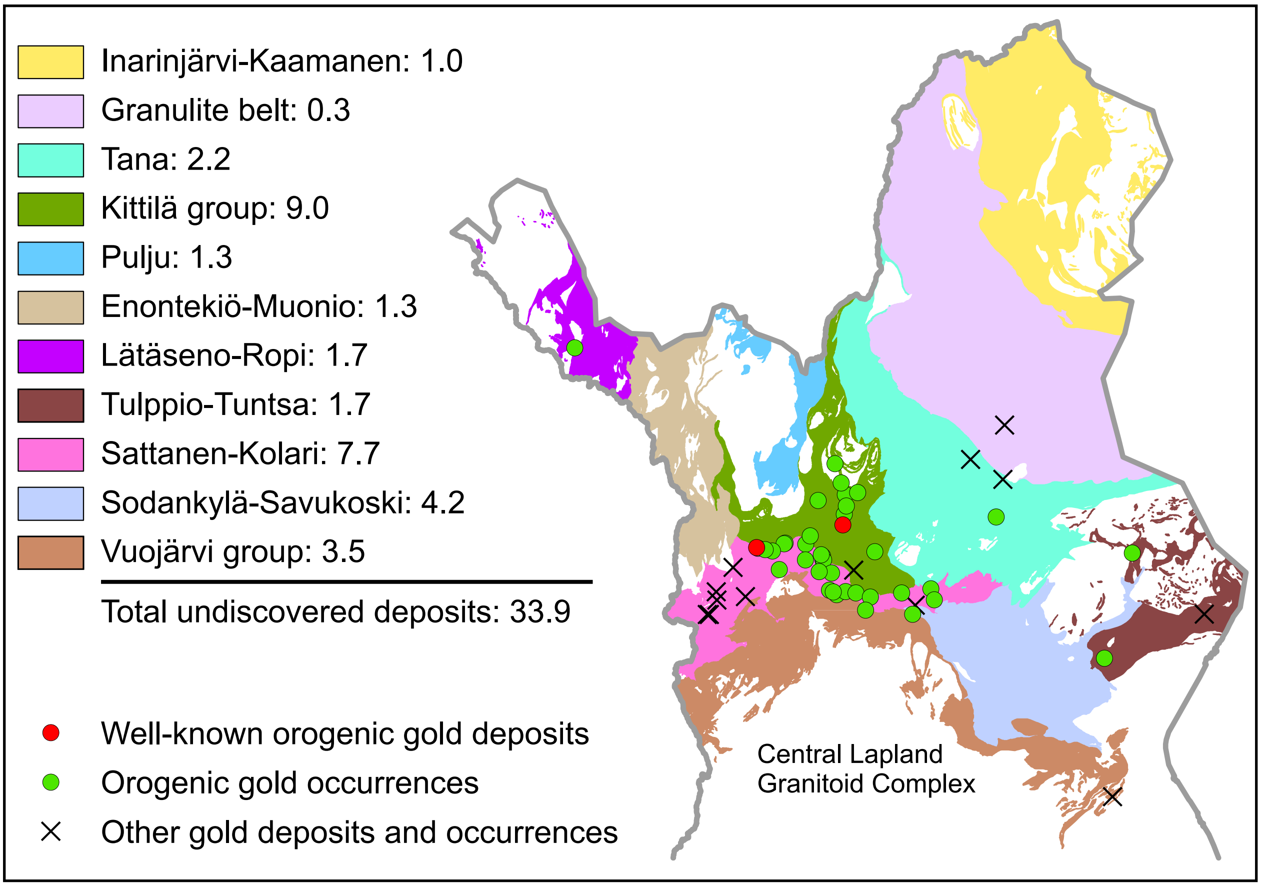

Fig. 3. Permissive tracts for orogenic gold deposits in the study area and the expected number of undiscovered deposits for each tract.

of the area; for example, Archaean tonalite-trondhjemite-granodiorite areas and young post-orogenic intrusions were excluded. The location of known orogenic gold deposits and occurrences, the existence of other indications of gold mineralization, the exploration history of areas, and comparison with the orogenic gold endowment in Precambrian greenstone belts elsewhere were also used as significant criteria for delineating and subdividing the tracts. The tracts cover 48 600 km^2, which is approximately 72% of the area north of the Central Lapland granitoid complex.

NUMBER OF UNDISCOVERED DEPOSITS

The number of potentially existing but as yet undiscovered orogenic gold deposits was estimated for each permissive tract (Fig. 3). The estimates were carried out in a workshop by experts with extensive knowledge of the geology of the tract areas and lengthy experience in gold exploration in northern Finland. The number-of-deposit estimates are consistent with the grade-tonnage model. Each expert estimated the number of undiscovered deposits at the 90%, 50% and 10% confidence levels. After discussion, either a consensus estimate was reached or arithmetic mean values of the figures of individual experts were used as the final estimate. Based on the estimates for individual permissive tracts, the expected (mean) number of undiscovered orogenic gold deposits in the area is 34 deposits.

GOLD RESOURCES IN UNDISCOVERED DEPOSITS

The assessment of gold tonnages in the undiscovered deposits was performed by Monte Carlo simulation using data from the grade-tonnage model and the estimated numbers of undiscovered deposits at the 90%, 50% and 10% probability levels. The simulation produces frequency distributions of ore and metal tonnages in the undiscovered deposits. Gold tonnages were estimated separately for each permissive tract and a grand total was estimated for all the tracts in the area (Table 1). The estimated total undiscovered gold tonnage in the area at 50% confidence level is at least 290 t.

Table 1. Estimated undiscovered orogenic gold resources in northern Finland.

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Au (t)	21	53	290	1400	2300	590	0.28	0.02
Ore (Mt)	7.8	22	150	1200	1900	420	0.25	0.02

t = tonnes, Mt = million tonnes

DISCUSSION

Comparison of the number of known deposits and the expected number of undiscovered deposits indicates that only about 5% of all the orogenic gold deposits in the area have as yet been discovered. On the other hand, the total estimated gold tonnage in the undiscovered deposits is not much greater than the total gold tonnage in the known deposits, suggesting that approximately 56% of the total gold endowment in the area is in undiscovered or poorly explored deposits. This discrepancy is due to the large Suurikuusikko deposit being one of the known deposits in the area. The known total pre-mining resource of 243 t of gold at Suurikuusikko is over 40 times greater than the resource of 5 t of gold for a median-sized deposit according to the grade-tonnage model.

Although most of northern Finland is covered by permissive tracts for orogenic gold, the known deposits and occurrences, as well as the estimated undiscovered gold resources, are concentrated within only a few tracts. Together, the Kittilä and Sattanen-Kolari tracts contain both the two well-known orogenic gold deposits and 32 of the 38 known orogenic gold occurrences in the area. These two tracts are estimated to contain, at the 50% confidence level, at least 180 t of undiscovered gold, which is 62% of the total estimated undiscovered orogenic gold resources in northern Finland. The Sodankylä-Savukoski and Vuojärvi group tracts immediately to the south and southeast of the Kittilä and Sattanen-Kolari tracts, although containing only two known gold occurrences, are estimated to be the next most promising areas for undiscovered deposits. In summary, the central and southern parts of the study area are estimated to have the highest potential for undiscovered orogenic gold in the region north of the Central Lapland granitoid complex (Fig. 3). These results are consistent with the findings of prospectivity mapping studies for orogenic gold in the Central Lapland Greenstone Belt area (Nykänen et al. 2008, 2011).

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ON THE USE OF THE DERIVATIVES OF POTENTIAL FIELDS IN INTERPRETATION OF GEOLOGICAL STRUCTURES

by

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Potential fields (magnetic and gravimetric) contain complete information concerning the distributions of magnetic properties and density of surrounding materials. If a rock body has both anomalous magnetic susceptibility and density, it can be modeled from both data. The magnetic field, however, attenuates more rapidly than the gravimetric field. For example, the gravimetric anomaly of a sphere decreases in proportion to the inverse square of distance, while the magnetic anomaly decays in proportion to the inverse cube of distance. For this reason, the deep parts of a homogenous anomalous body can be interpreted more reliably from gravimetric than from magnetic data. Usually the source bodies of magnetic and gravity anomalies differ from each other and the contacts differ as well. Anomalies are caused by content of minerals with anomalous susceptibility or density in the rock. Thus the contacts of anomalous magnetic or gravity bodies do not necessarily coincide with contacts of rock types.

Many derivatives (horizontal and vertical derivatives, various filterings, upward and downward continuations etc.) of potential fields can be used in the interpretation of geological structures (Fig. 1). Even with large amounts of data, efficient computers and processing software, make it is possible to obtain automated interpretations quickly. Figure 2 illustrates an automatically generated 3D-model of a gabbro body. These interpretations, however, must be used with great caution. It is important to consider the original data density to avoid interpretation of quasi-anomalies caused by interpolation. Usually, before calculation of derivatives it is necessary to remove the effects due to noise e.g. by filtering or upward continuation.

In magnetic investigations the quantity usually measured is Total Magnetic Intensity (TMI). TMI contains induction caused by both the ambient geomagnetic field and permanent magnetization of the rock. TMI has the same direction as the geomagnetic field unless permanent magnetization has a different direction. TMI can therefore be reduced to simulate the situation at the Magnetic North Pole (RTP) where the field is vertical, or at the Magnetic Equator (RTE) where the field is horizontal. In these cases anomalies caused by non-remanent vertical structures are symmetrical and are more readily comprehended in qualitative interpretation. It should be realized that at the Equator a magnetic 2D-structure striking

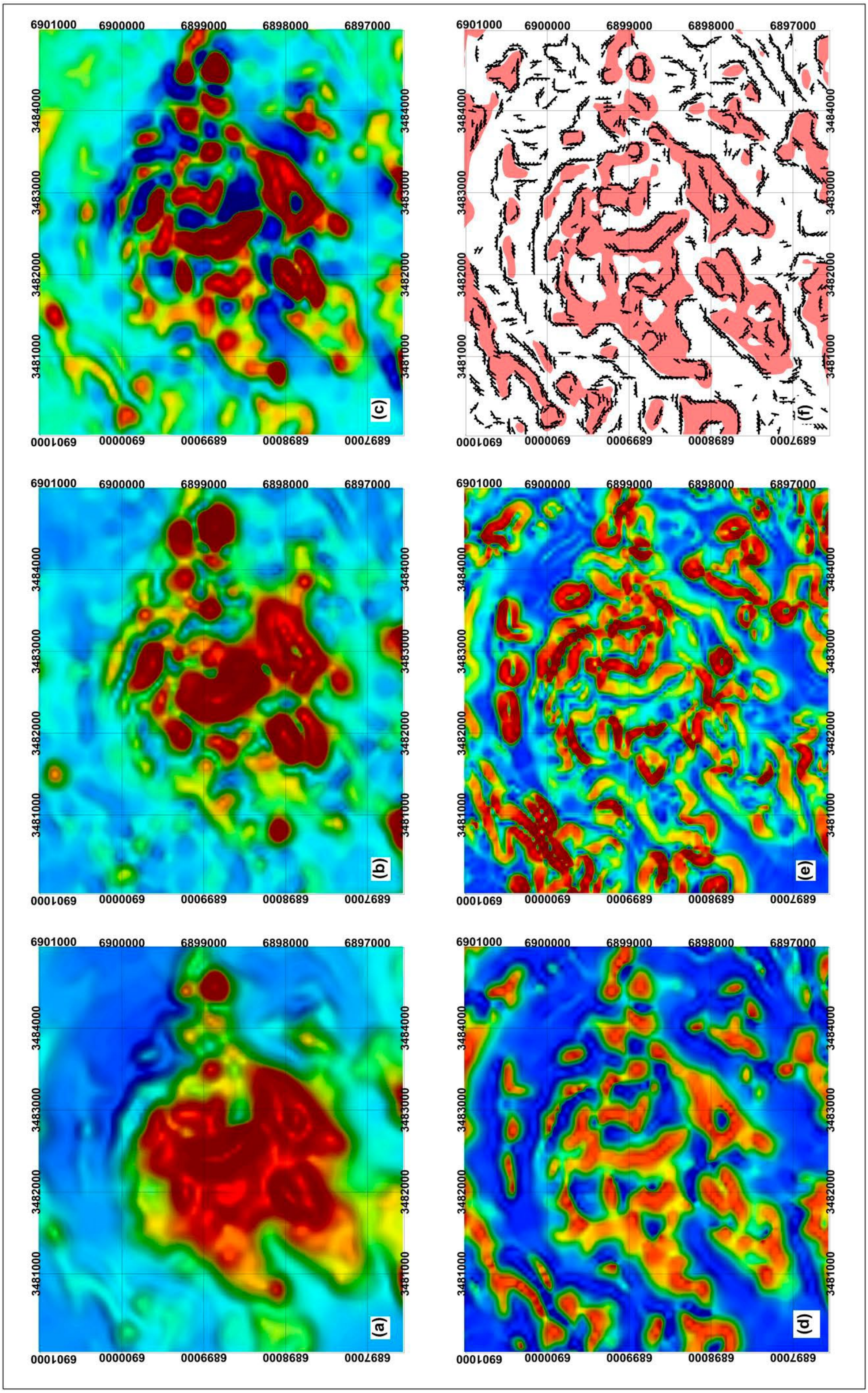

Fig. 1. Airborne total magnetic (TMI) induction (a) of Ylemmäinen gabbro in Pieksämäki. Analytical signal of TMI (b), vertical derivative of TMI (c), tilt derivative (TDR) of TMI (d), horizontal derivative of TDR (e) and classified TDR with solutions of automatic source edge detection (black symbols) (f) showing contacts and magnetically anomalous parts of base rock (red areas).

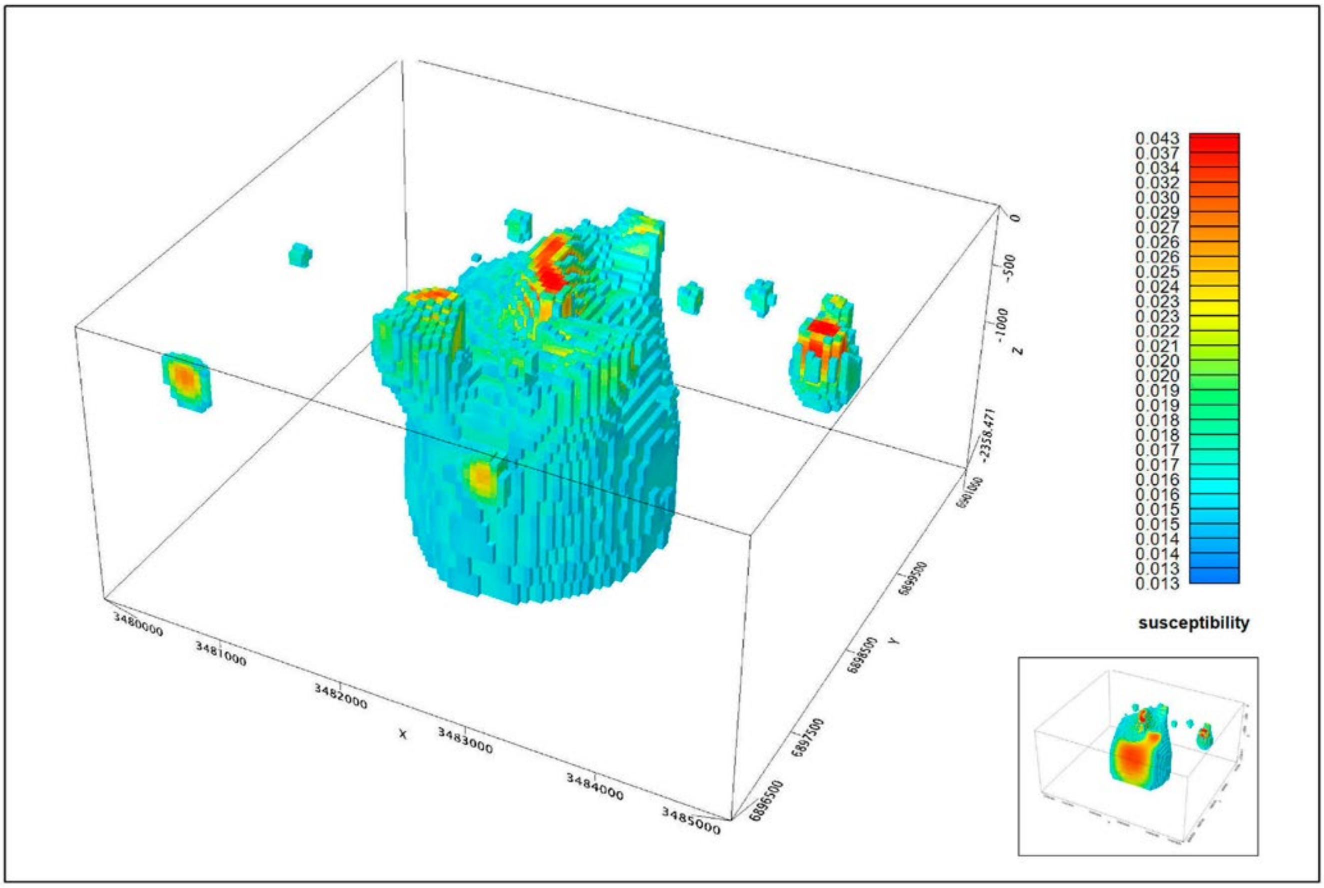

Fig.2. Non-constrained 3D-voxel inversion of Ylemmäinen gabbro.

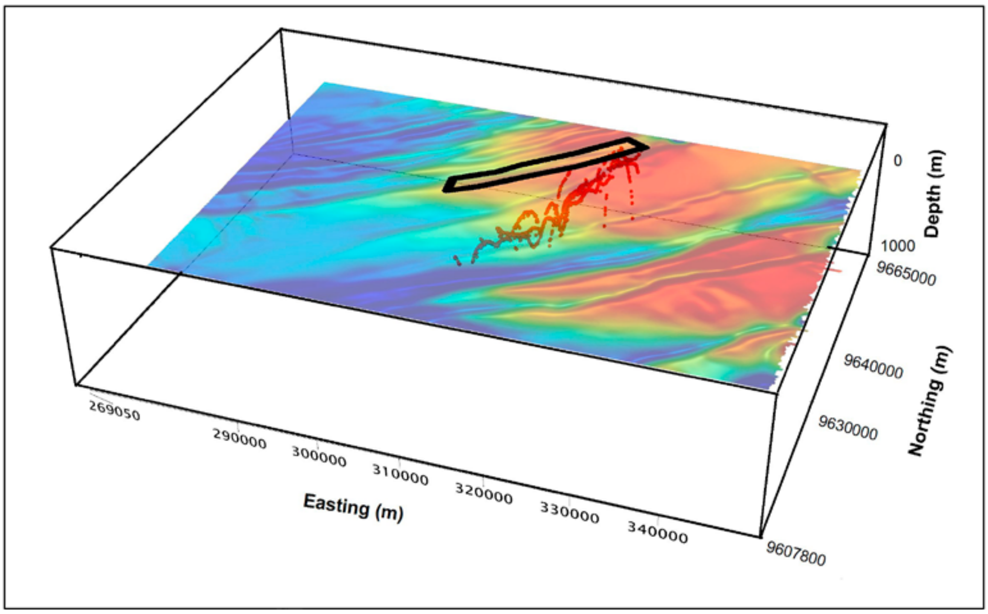

Fig. 3. Total magnetic induction of Biharamulo area in western Tanzania. Fading of anomalies of magnetic dykes towards south-west is caused by covering younger non-magnetic formations (sediments and flood basalts). SPI™-solutions (x,y,z) for one dyke are indicated by red symbols (by the courtesy of Geological Survey of Tanzania).

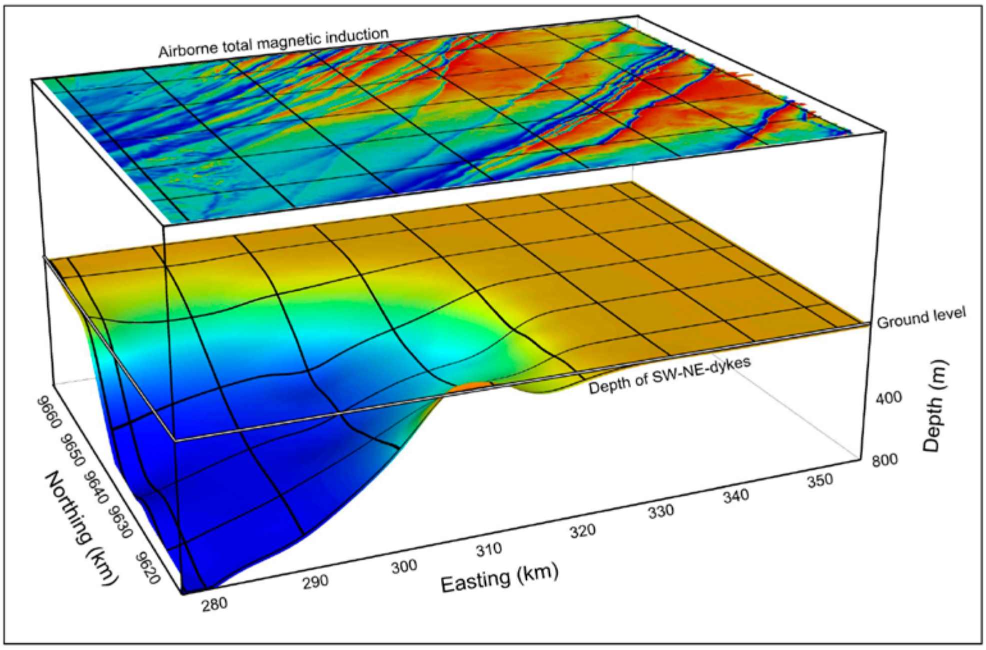

Fig. 4. Interpretation of depth to the bottom of young rock formation at Biharamulo area, western Tanzania. The surface has been obtained combining results of quantitative modeling and SPI™-solutions for depths of magnetic dykes (by the courtesy of Geological Survey of Tanzania).

magnetic north, does not cause any TMI anomaly regardless of the susceptibility. In many cases RTP amplifies small anomalies or noise causing results to overshoot. Therefore, near the Magnetic Equator (+/- 20 degrees) reduction to magnetic pole should be avoided, or at least an amplitude correction must be used (MacCleod et al. 1993).

The analytical signal (AS) is the amplitude of the total TMI derivative and is almost invariant with respect to dip and remanence of the source body. It is always positive and can therefore be used in locating boundaries of source bodies.

Tilt derivative (TDR) is the tilt angle (radians, -π/2 to π/2) of TMI (Miller & Singh 1994 Verduzco et al. 2004, Salem et al. 2008), which is useful in locating anomalous formations and in qualitative interpretation of geological structures. Its horizontal derivative (TDR-HD) is utilized in the Source Parameter Imaging procedure (SPI™) integrated in Oasis montaj (Thurston & Smith 1997). SPI™ solves automatically the horizontal and vertical locations of 2D-magnetic sources. This procedure is especially suited to areas where non-magnetic formations cover magnetic sources (Figs. 3 and 4) and seems to produce better results than Euler deconvolution (Keating & Pilkington 2004) or An-Eul-deconvolution (a combined analytical signal and Euler deconvolution method) (Salem & Ravat 2003), both of which are options in Oasis montaj. The source edge detection (SED) procedure in Oasis montaj automatically detects horizontal locations of edges of anomalous formations from gridded magnetic or gravimetric data (Fig. 1f) (Blakely & Simpson 1986).

Sometimes surveys have been carried out at different altitudes. The same results can be simulated by continuing the measured data upwards or downwards. By fitting the anomaly of the model simultaneously to data from different elevations it is possible to significantly reduce the degree of freedom of solutions (Figs. 5 and 6).

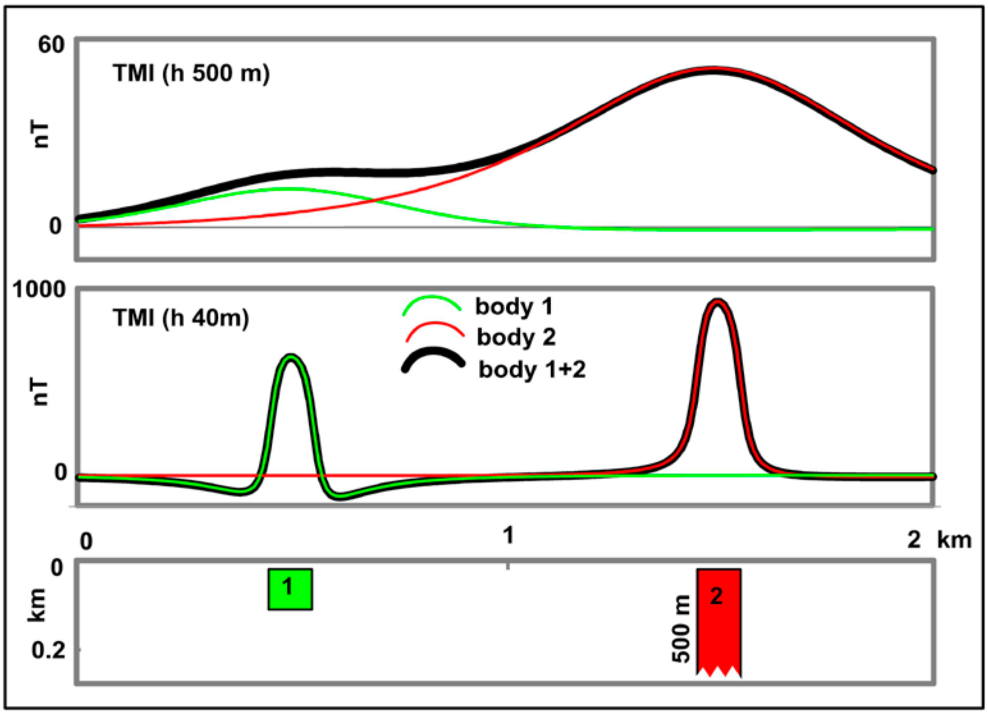

Fig. 5. Comparison of magnetic anomalies of 100 m deep and 2000 m deep plates at elevations of 40 m and 500 m above ground level. For both plates, the depth to top is 20 m and susceptibility 0.05 SI.

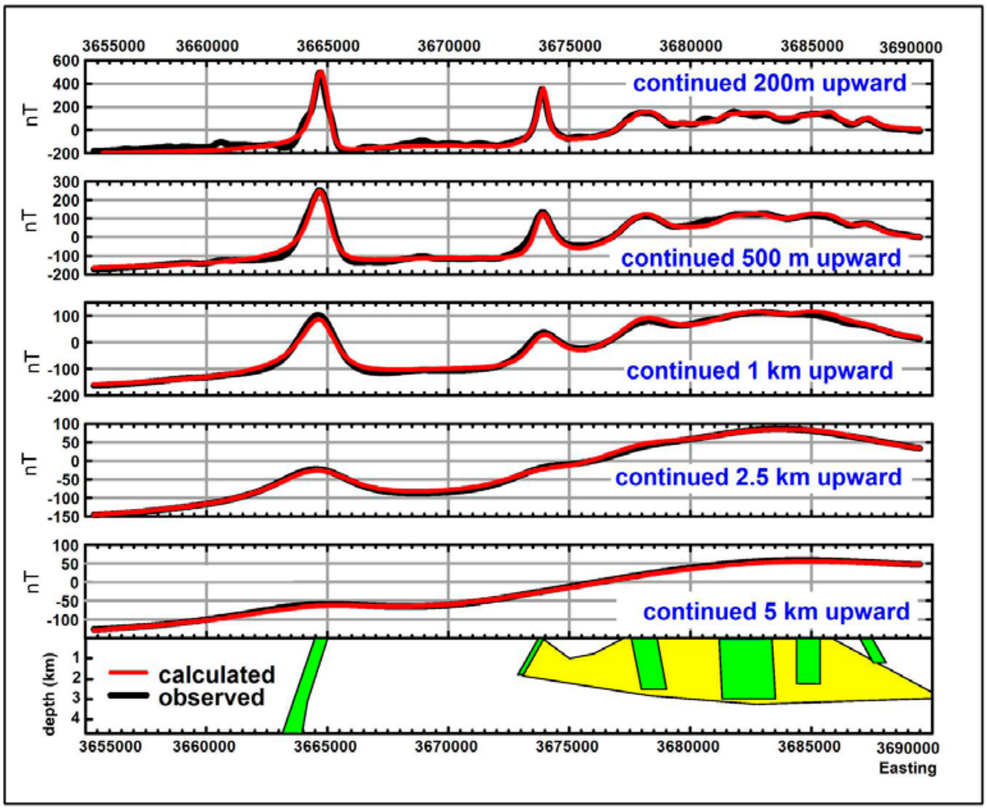

Fig. 6. Airborne magnetic modeling (Onkamo–Tuupovaara). The same model fitted to total magnetic induction at five different levels of upward continuation.

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ON THE PROSPECTING FOR REE IN THE TANA BELT, NORTHERN FINLAND

by

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INTRODUCTION

The so-called Tana Belt, which forms an arcuate zone along the southern and western margin of the Lapland Granulite Belt is visible as an anomalous zone on many geophysical maps. For example, in airborne magnetic images, several parallel anomaly maxima, tens of kilometers in length, are evident. Even though the intensities of the maxima are not exceptionally high, they are higher than those in the magnetically flat granulites to the northeast, and more variable than in the volcanic terrain towards the southwest. Electromagnetic anomalies are somewhat complicated, partly due to the abundance of swamps and lakes. Radiometric maps, instead, reveal interesting features that have much in common with the magnetic image. The magnetic high along the Tana Belt is accompanied by a maximum in potassium, uranium and thorium contents, whereas the granulite area shows considerable variation in terms of radionuclide content ratios. On the geological map (Fig. 1), the Tana Belt is seen to consist of long and narrow arkosite and gneiss formations. From the point of view of mineral prospecting, the Tana Belt is interesting as the REE concentrations in till geochemical (Fig. 2) and lithogeochemical datasets are anomalous, while falling to regional background levels towards the northeast and southwest.

Common REE containing minerals, such as monazite, xenotime and allanite, typically contain Th and commonly also U in their crystal lattices. Even though the REE elements are very dense (density 5000–10000 kg/m^3) and some have very high magnetic susceptibility, they usually do not affect the bulk physical properties of the host rock. Electric conductivity of REE-bearing minerals is also high, although two orders of magnitude lower than that of copper, but as they do not form sulfide-like macroscopic conductive meshes, their effect on host rock conductivity is low. Accordingly, geophysical methods based on density, magnetism or electric conductivity, can be used only indirectly in exploration, by tracing potential host rocks and their properties; for example, magnetic and electromagnetic methods can be useful in locating REE deposits associated with weathering. Gamma spectrometry, which can detect decay products of Th and U, offers an almost direct method for prospecting for REEs.

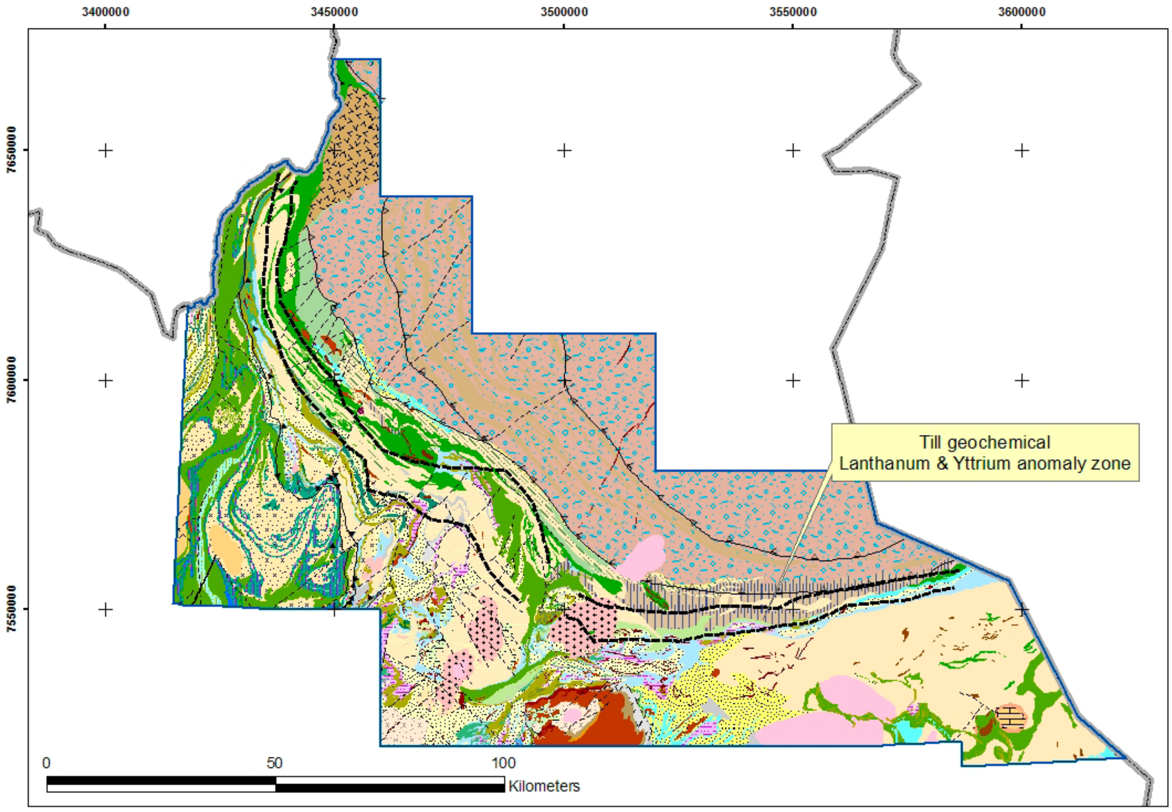

Fig. 1. Geological map of the study area, showing the location of a geochemical REE anomaly zone in the Tana Belt (Bedrock of Finland – DigiKP).

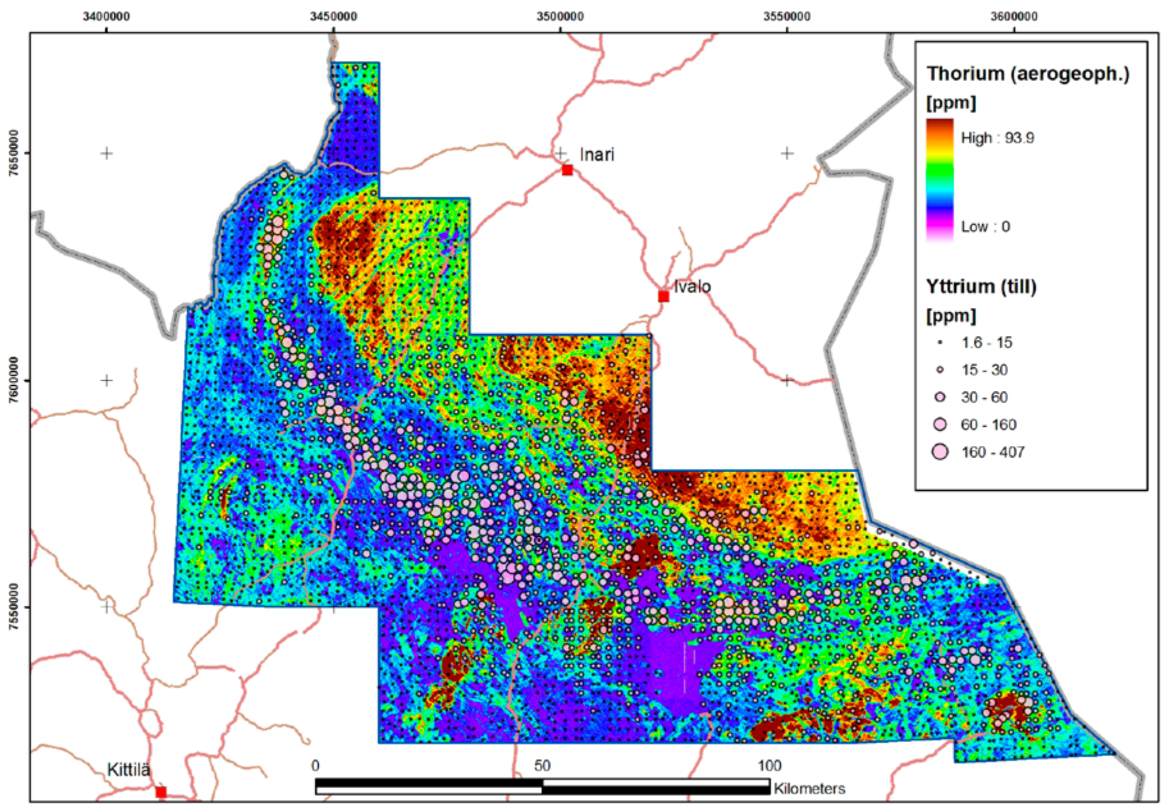

Fig. 2. Airborne thorium map with yttrium content from till geochemistry (Roads from the National Land Survey of Finland Topographic Database 08/2012).

RESULTS

In the airborne radiometric data, Th abundances are relatively high in the Lapland Granulite Belt, but REE contents in till and rock geochemistry are low. The highest Y anomalies in till are located outside the granulite belt in a marginal area where a narrow radiometric Th anomaly is also evident. Anomalous zones of lanthanum and yttrium are also coincident, although the highest lanthanum values are found somewhat further east, outside the Riestovaara granite.

The average REE contents of different rocktypes in the study area, obtained from the Rock Chemical Database of Finland (Rasilainen et al. 2007), are shown in Table 1. The highest REE concentrations are in gneissic granites and granitic gneisses, while the lowest values are in mafic and ultramafic volcanic rocks, gabbros, anorthosites and quartzites. Comparison between the distribution of rocks units, extracted from digital bedrock map of Finland (Bedrock of Finland – DigiKP. Vesion 1.), and till geochemical anomalies (Salminen 1995) shows that the highest La and Y anomalies are associated with arkose gneisses (mean/max La 49/416 ppm and Y 31/205 ppm) and quartz-feldspar gneisses (mean/max La 45/178 ppm and Y 26/84 ppm). Carbonatites at Sokli also correspond to very high REE anomalies, although only 3 sample points are situated with thin area of the Sokli massif.

Principal component analysis (PCA) was performed for eliminating redundancy and emphasizing variances within till geochemical La, Y and Sc raster data. In Figure 3 a ternary PCA image from the anomalous REE zone is shown. In general La and Y anomalies correlate well in yellow and red areas. The highest Y anomalies are, however, located in the western part of the anomaly zone (shown yellow on the map), indicating HREE potential in the bedrock. The highest La anomalies are located in the eastern side of the zone (shown red), indicating LREE potential. The highest Sc concentrations are situated in the granulite belt next to the La and Y anomaly zone, shown as light blue on the ternary map.

Table 1. Average REE contents of different rock types in the study area (analyzed by ICP-MS, 236 samples), from the Rock Geochemical Database of Finland (Rasilainen et al. 2007)

ROCKTYPE	Count	Y [ppm]	La [ppm]	Sc [ppm]	HREE total [ppm]	LREE total [ppm]	REE total [ppm]
GNEISSIC GRANITE	2	92	94	4	58	411	469
GRANITIC GNEISS	17	39	67	4	25	273	298
QUARTZ-FELDSPAR GNEISS	18	62	55	5	38	247	285
GRANITE	15	20	68	4	13	247	260
MICA GNEISS	17	32	46	6	21	187	208
MICA SCHIST	4	23	46	25	17	187	204
GRANULITE	55	31	44	19	19	182	202
GNEISS	12	57	35	13	34	167	201
QUARTZ DIORITE	12	14	32	18	11	137	148
GRANODIORITE	2	6	23	4	4	88	93
AMPHIBOLITE	19	23	9	42	14	46	60
HORNBLENDE GNEISS	6	16	10	35	10	49	59
MAFIC VOLCANIC	17	23	7	42	14	39	53
GABBRO	8	16	7	36	10	35	45
QUARTZITE	11	5	8	3	3	33	36
ULTRAMAFIC VOLCANIC	14	8	3	22	5	18	23
ANORTHOSITE	7	2	2	3	2	11	12

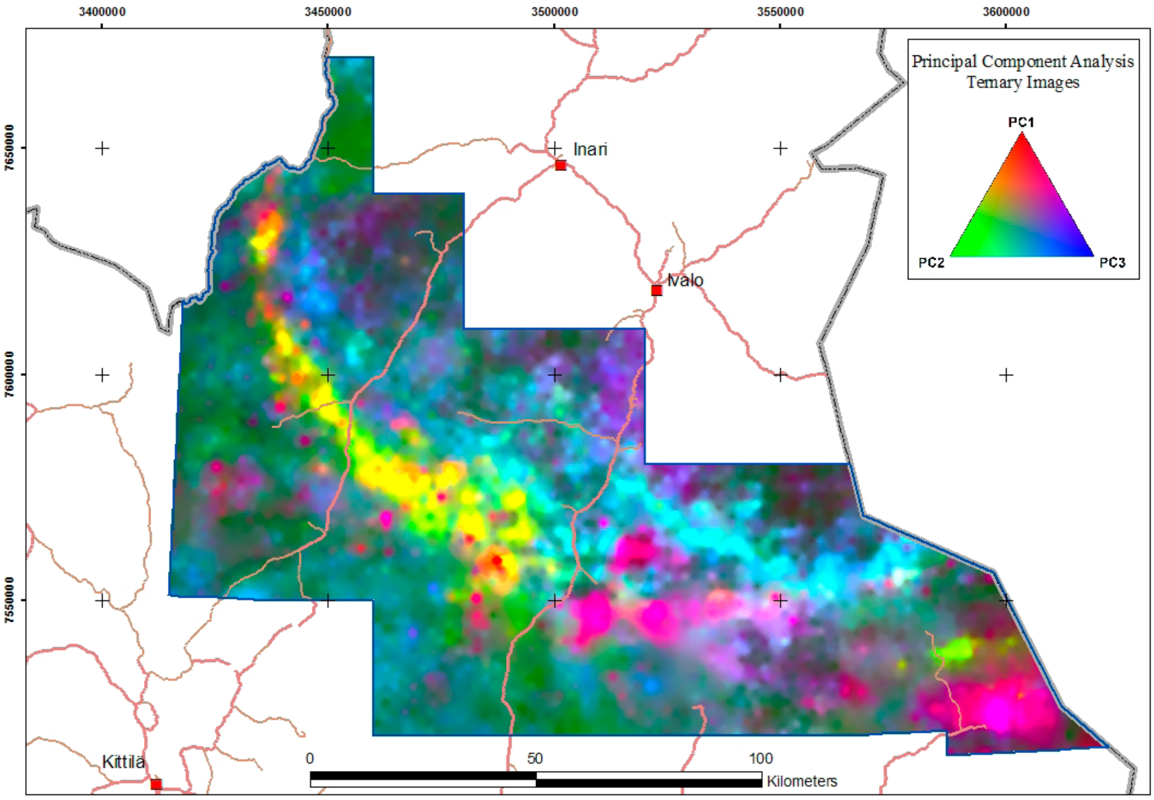

Fig. 3. Ternary image of principal component analysis made from till geochemical La, Y and Sc data, showing the anomalous REE zone (Roads from the National Land Survey of Finland Topographic Database 08/2012).

CONCLUSIONS

Based on the correlations of lithogeochemical and till geochemical data sets with bedrock map data, the REE anomalous zone in the Tana Belt is related to arkosic and quartzo-feldspathic gneisses. The distributions of these rocks together with the REE-enriched zone are also seen as anomalous areas in the airborne radiometric data. This suggests that the radiometric and magnetic maps can be used for further REE exploration in the Tana Belt.

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NEW METHODS FOR GEOCHEMICAL EXPLORATION AND ORE POTENTIAL MAPPING USING TILL IN GLACIATED TERRAIN, FINLAND

by

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New sampling techniques and analytical methods for till geochemistry and heavy minerals in exploration are being investigated by GTK (Finland), with the aim of developing new applications in regional and/or target-scale exploration. The tests are carried out as a part of on-going mineral potential mapping and hi-tech mineral exploration projects as well as under the new Tekes Green Mining project 'Novel technologies for greenfield exploration' (NovTecEx) in the Savukoski–Pelkosenniemi region, eastern Finnish Lapland (Fig. 1). Testing and development include different types of 1) sampling and sampling techniques for large, representative till geochemical and heavy mineral samples, 2) advanced and partially automated indicator mineral research, 3) portable and on-line XRF methods for till and weathered bedrock samples from test excavations and drill core samples and 4) rugged field computers together with GPS-units for data acquisition and navigation in the field (see http//:www.tekes.fi/ohjelmat/GreenMining; Sarala et al. 2012).

Anticipated benefits of the research will include finding new solutions for surficial exploration using till and weathered bedrock in environmentally sensitive areas. An important aim is to minimize environmental impact due to exploration activities in areas of thick glaciogenic overburden, in peatlands and in nature reserves. At the same time, the focus is also on decreasing analytical costs and increasing sampling efficiency. A preliminary knowledge for all of the methods which will be tested or developed are already known to be suitable for exploration purposes in glaciated terrain, although the detection limits may impose some constraints on their applicability. For example, portable XRF methods are only suited to determination of elevated abundances for major elements and some trace elements. However, in the case of till as sampling material, the haloes of indicator elements and minerals are larger and easier to detect, and comparative examination of element abundances is commonly sufficient for identifying mineralization or mineralized alteration zones in bedrock, as well as for direct target-scale sampling and study.

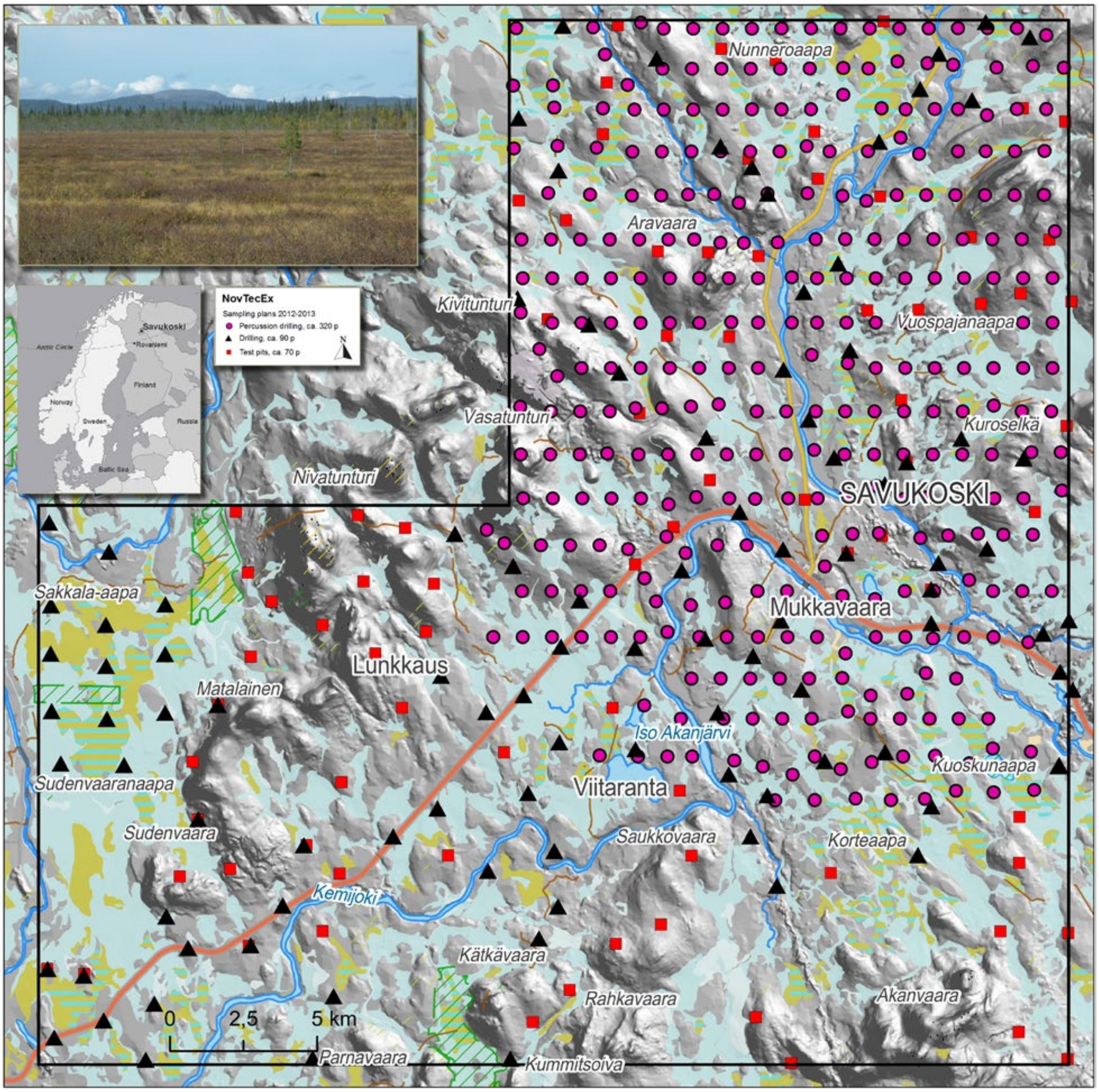

Fig. 1. Study area and the sampling point networks of the NovTecEx project in eastern Finnish Lapland. Contains data from the National Land Survey of Finland Topographic Database 2012.

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RARE EARTH ELEMENT EXPLORATION AND POTENTIAL IN NORTHERN FINLAND

by

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INTRODUCTION

GTK has a research project (2009–2012) evaluating the exploration potential of hi-tech metals in Finland, including Li, Ti, In, Ga, Ge, Nb Ta, Te and rare earth elements (REE). Among these metals the REE play a particularly critical role in numerous hi-tech applications and environment friendly energy technologies, e.g., hybrid and electric cars, solar panels, wind turbines, phosphors, magnets, LCD screens, mobile phones and computers. In the EU and other industrialized countries REE are among the most critical metals in terms of availability, mainly because there is currently no mining for REE in Western countries and as much as 97% of global production is controlled by China.

During the current project, available relevant data from published literature, previous reports, various databases, and from reassaying of existing drill cores have been combined with new data from recent till geochemical, till heavy mineral and geophysical surveys, geological mapping and drilling, in order to select potential target areas for exploration. The new exploration efforts have been directed mainly to northern Finland, focusing especially on the heavy rare earth elements (HREE), for which future industrial demand is expected to grow particularly quickly.

Rare earth elements are quite common in the Earth's crust, but usually at concentrations that are greatly below minable grades, the average total concentration of the REE in the Earth's crust typically being between 150 to 220 ppm (Long et al. 2010). At the moment, the main global sources of REE are from carbonatites and alkaline rocks, placer deposits and residual deposits such as the ion-adsorption clays, which are formed by deep, intense weathering, typically from igneous rocks. Other potential deposit types under exploration or feasibility studies include iron-oxide copper-gold deposits (e.g. Olympic Dam), marine phosphates and deep sea iron-manganese nodules. Light REE (La-Eu) tend to concentrate in carbonatites whereas the least available heavy REE (Gd-Lu) are relatively more abundant in alkaline granites and pegmatites, from which they may also be enriched to form economic deposits by weathering processes.

The nearest occurrences to Finland that have potential for economic REE are associated with the intrusions of the Devonian Kola alkaline province, in particular the Lovozero and Khibina intrusions. The Sokli carbonatite and Iivaara alkaline complexes in Northern Finland also belong to the Kola alkaline province (Vartiainen 1980, O'Brien et al. 2005).

Available regional geochemical and rock geochemical data (Salminen 1995, Rasilainen et al. 2008) show that in northern Finland there is a particularly interesting zone of high Y and La-anomalies along the arcuate margin of the Palaeoproterozoic Tana Belt (Fig. 1). High La-anomalies are also associated with the Sokli Complex and within the Central Lapland Granite area, in the latter case mainly related to intrusions of post-orogenic appinite (a rock type belonging to the calc-alkaline lamprophyre clan) (Figs. 1 and 2).

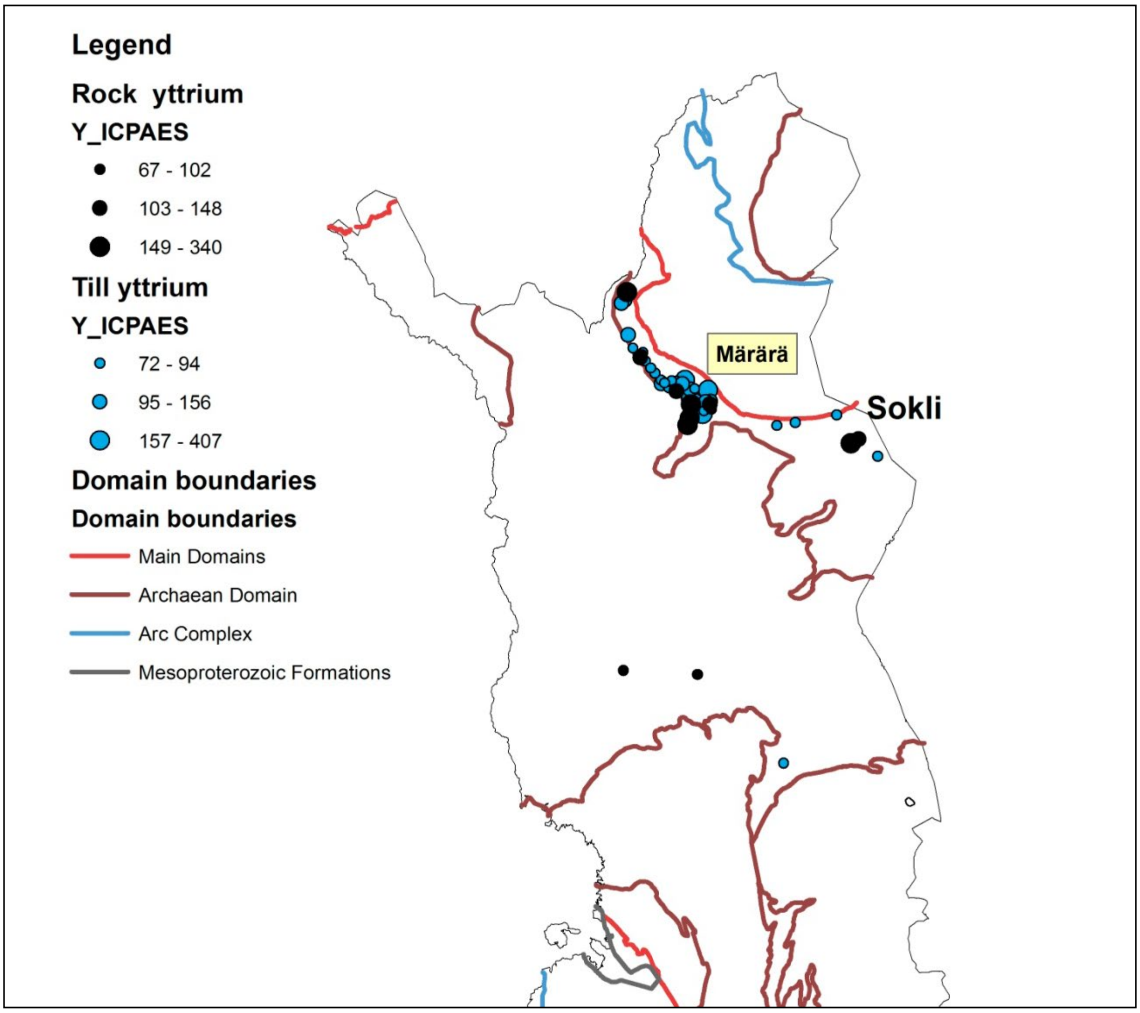

Fig. 1. Yttrium anomalies in regional till and rock geochemical data indicate potential HREE areas in the Tana Belt and Sokli areas in northern Finland.

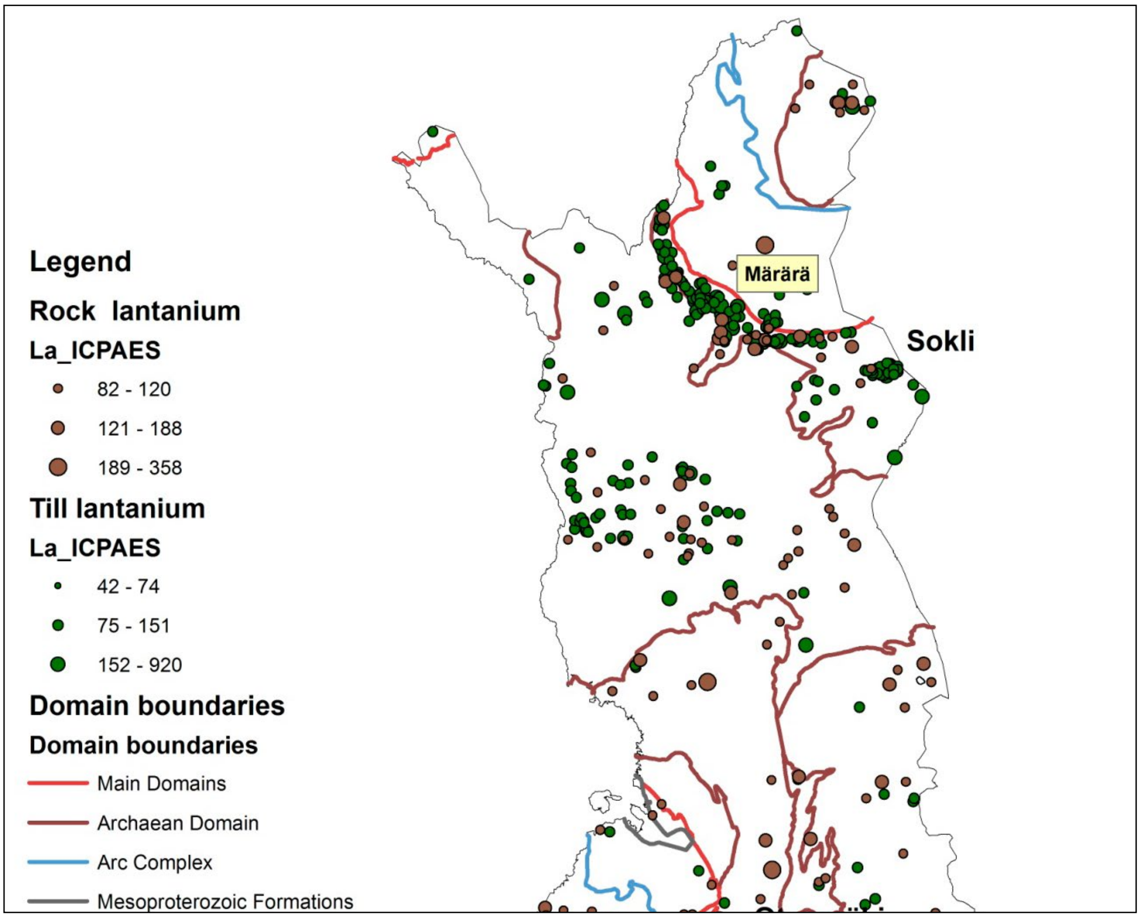

Fig. 2. Lanthanum anomalies in regional till and rock geochemical data indicate several potential LREE areas in northern Finland.

RESULTS

Systematic geochemical surveys and diamond drilling campaigns have been carried out in the Mäkärä and Vaulo areas, within the Tana Belt (TB) and within the fenite zone of the Sokli complex, while the Vanttaus, Lehmikari and Suhuvaara appinites, the Kortejärvi-Laivajoki carbonatite and Iivaara alkaline complex have all been targeted for investigation. In addition, the Palkiskuru albitite near Enontekiö and the Honkilehto and Uuniemi albite-carbonate rocks at Kuusamo have been studied for their REE-mineralogy and chemistry using samples from a few drill cores or outcrops (Fig. 3.)

In the Mäkärä Au-REE prospect area, south of the Lapland Granulite Belt, the bedrock is poorly exposed but the prospect is related to a NW-shear zone in an arkosic gneiss which is overlain by a 5–30 m thick layer of kaolinitic saprolite. This zone has potential for ionic adsorption-type HREE and gold occurrences (Sarapää & Sarala 2011). The saprolites that are derived from pyrite-bearing arkosic gneisses and gold-quartz-hematite veins correlate well with positive electromagnetic anomalies. Au contents, in both till and weathered bedrock, are highest in areas that are known to contain hematite-rich zones in the underlying bedrock. The Y and Au anomalies do not coincide, but both are roughly located within the arkosic gneisses of the TB. On the other hand, the highest La and Y contents in till correlate well with the airborne radiometric Th-gamma radiation maxima . The mean REE content in saprolite at Mäkärä was 0.05% (max. 0.1%) and at Vaulo up

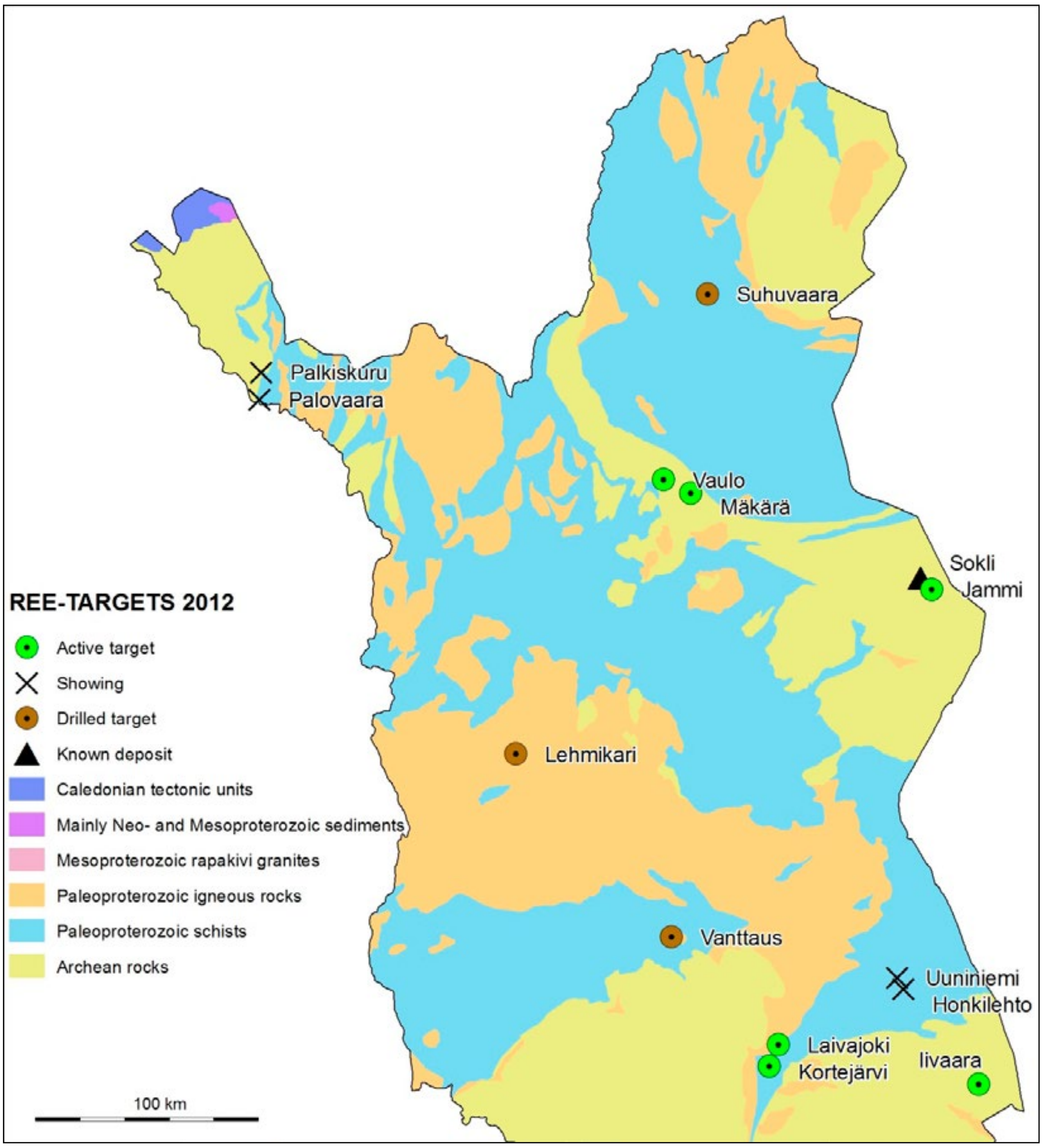

Fig. 3. Recent REE-exploration targets by GTK on a simplified geological map of northern Finland.

to 0.4%. The latest drilling results also indicate that REE contents were higher at Vaulo than at Mäkärä.

REE-exploration within the fenite zone of the Sokli carbonatite started in the Jammi area (Kontio & Pankka 2006), where drilling results revealed REE-enrichments in narrow late-stage carbonatite veins. The bedrock in this area consists of Archaean mafic volcanic rocks and tonalitic gneisses, which are intruded by the Devonian Sokli carbonatite, causing areally extensive and intensive albitic fenitization of the country rocks (Al Ani & Sarapää 2011). Most of the LREE is found in carbonates and apatite although REE-rich accessory phases such as monazite and ancylite (Ce) significantly influence the REE distribution in samples if they are present in particularly large amounts. Other observed REE-bearing minerals include Sr-apatite, bastnäsite (Ce), strontianite, baryte and brabantite. REE grades in the carbonatite veins range from 0.11–1.83%, including 0.11–1.81% LREE and 0.002–0.041% HREE.

Mineralogical and chemical evidence demonstrates that hydrothermal processes were responsible for the REE mineralization. During late-stage processes, apatite and carbonate minerals were replaced by various assemblages of REE–

Sr–Ba minerals. Importantly, the data suggest that REE from apatite could be a potential by-product of phosphate production in the Sokli area. Overall, the recent results of the systematic till and weak leaching geochemical surveys from soil indicate good potential for REE in the Sokli fenite zone.

Postorogenic appinites, first identified in Finland by Mutanen (2011), are widespread within both the Central Lapland granitoid complex (CLGC) and in the Lapland granulite belt. The studied appinite intrusions at Suhuvaara, Lehmikari and Vanttaus mainly comprise dioritic to syenitic rocks. These rocks are characterized by high contents of Ba, Sr, Zr, P and LREE, with REE contents in syenitic members ranging up to 1000 ppm and phosphate abundances in mafic members up to 3.5% P_2O_5 (Lauri et al. 2011). Given the high background P and REE levels, the appinite intrusions clearly have potential for P-REE-deposits, especially noting the rather large size of several of the intrusions, such as Vanttaus.

SUMMARY

The REE potential of Northern Finland has been studied by the GTK since 2009. Several areas with promising potential have been located, based on compilations of existing data and new field and laboratory work. The results indicate highest potential for REE in carbonatites and alkaline rocks, including their possible fenite zones and weathering products.

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MINERAL POTENTIAL OF THE SVECOFENNIAN HÄME BELT, SOUTHERN FINLAND

by

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The Svecofennian Häme belt is part of the Paleoproterozoic Southern Finland arc complex (Fig.1). The Bedrock lithology, geochemistry and mineral occurrence data are being revised during a 2-year project at the Geological Survey of Finland, the goal being an assessment of the mineral potential of the Häme Belt, which is one of the least explored schist belts in Finland. The main method for acquiring new data is till geochemical surveying, within the area between Forssa and Hämeenlinna. Some of the observed anomalies are being checked by detailed geochemistry, heavy mineral studies, bedrock mapping, ground geophysical surveys and drilling. In addition, regional interpretations of geological and geophysical structures, petrological studies based on the nationwide lithogeochemical data set, and prospectivity analysis are used as methods for estimating regional mineral potential. One result of this work will be a project map with structural interpretations of the geological structure of the region. The mineral potential of the Häme Belt was previously reviewed by Tiainen and Viita (1994) and Lahtinen and Lestinen (1995).

The Häme Belt is located between the Pirkanmaa and Uusimaa Belts (Kähkönen 2005). A large part of the late Svecofennian Southern Finland Granite Migmatite Belt occurs within the area of the Häme Belt as a result of tectonic stacking. A tectonic terrain boundary defines the northern margin of the Häme Belt. The southern border of the Häme Belt is more complex and the east-west trending Hyvinkää–Mäntsälä mafic intrusive complexes and surrounding volcanic rocks are here included within the Häme Belt. To the west of the Hyvinkää layered gabbro, the southern border of the Häme Belt is marked by mica gneisses with carbonate rock intercalations belonging to the Uusimaa Belt. Further west, the boundary is determined by the geochemical composition of the volcanic rocks, which are island arc calc-alkaline rocks in the Häme Belt, whereas on the western side and to the south the volcanic rocks are typically MORB-type tholeiites.

The Häme Belt is characterized by both volcanic and intrusive rocks. The volcanic rocks of the Häme Belt are divided into two spatially and compositionally different groups, the Forssa Suite and the Häme Suite (Hakkarainen 1989, Lahtinen & Lestinen 1996). The Forssa Suite is regarded as older than the Häme Suite (Hakkarainen 1994). Arc type rocks of Forssa Suite are mainly well-preserved

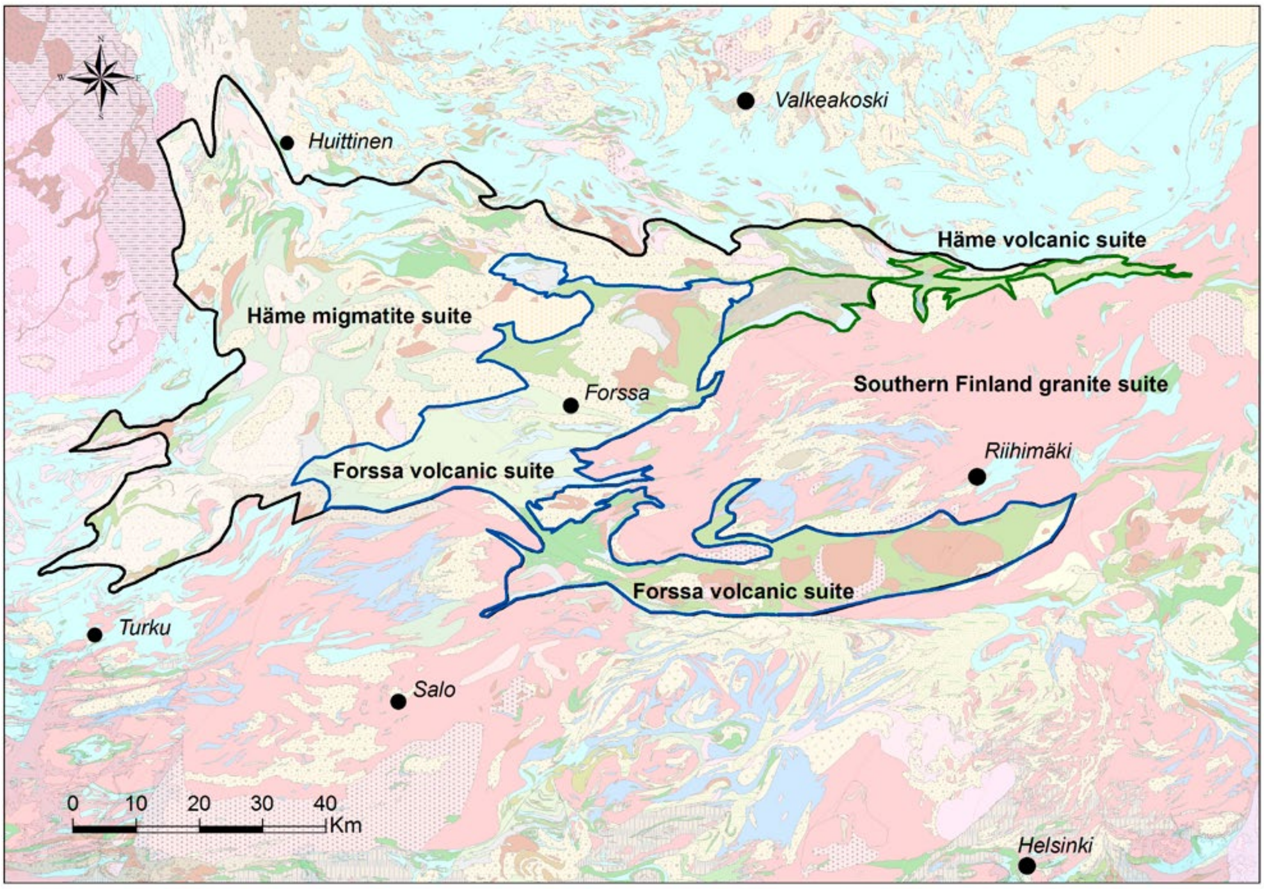

Fig. 1. Bedrock geological map of the Häme Belt (Bedrock of Finland–DigiKP). The Häme and Forssa Ssuites are outlined.

whereas banded amphibolites in the western part of the Häme Belt are assigned to the Häme migmatite suite. Intermediate and felsic rocks dominate in the Forssa Suite, and alteration zones, with sericite and cordierite-antophyllite rocks, critical for synvolcanic hydrothermal sulphide ore formation, are also locally present. Volcanic rocks in the Häme Suite are mainly mafic in composition and texturally are dominantly subaerial, originating mainly from fissure type eruptions during early stage rifting. According to contact relations the Häme suite is syngenetic with the layered Forssa gabbro intrusion. New till geochemical data indicate that the Häme suite close to the contact of the Forssa gabbro may have potential for gold mineralization (Huhta 2013).

Some of the granodiorite, tonalite and gabbro intrusions of the Häme Belt are evidently coeval with hypabyssal and volcanic rocks, including the Kedonojankulma tonalite intrusion, which hosts porphyry type Au-Cu mineralization (Tiainen et al. 2011).

An extensive area in between the Häme suite and the Hyvinkää–Mäntsälä gabbro complex (including volcanic rocks) is characterized by late orogenic granites. Locally this late orogenic granite area is strongly magnetic and contains enclaves of gneisses metamorphosed in the granulite facies. This part of granite-migmatite complex has been interpreted as a tectonic window of deeper crust (Nironen et al. 2006, Tiainen & Viita 1994). Such granites are considered critical for HiTech metals, and the Somero–Tammela area is one of the major compex pegmatite provinces in Finland, and is known to contain indication of Li mineralization.

Exploration in the Häme Belt has focused mainly on Au, Cu, Zn, Li and W, and mining in the area currently includes gold at the Jokisivu mine and carbonate rocks from Punola and Matkusjoki at Vampula; all three of these deposits are within the municipality of Huittinen (Fig. 2). In addition to the Jokisivu deposit, other types of orogenic type gold occurrences have been found in mafic intrusive rocks of the Huittinen area (Grönholm & Kärkkäinen 2013). Some other Au mineralized areas in the Häme Belt have been found in the so-called Somero–Tammela zone (Satulinmäki, Huittinen, Sukula) and the Latovainio geochemical Au-As-Sb-Te-Cu anomalous area north of Forssa (Kedonojankulma, Arolanmäki, Liesjärvi). The occurrences at Latovainio are genetically related to granitoids, and one, Kedonojankulma, is classified as porphyry type (Tiainen et al. 2011). VMS-type Zn-Cu occurrences are also present in the Häme Belt at Tupala (Somero), Kiipu (Jokioinen), Kuuma (Jokioinen), Leteensuo (Kalvola), Katumajärvi (Hämeenlinna) and Pääjärvi (Lammi) (Papunen 1990). Tungsten and tin were investigated in the Hämeenlinna area during 1990's by Rautaruukki Oy (Kinnunen 1987, 1988, Peuraniemi 1985) and results indicate that follow-up studies are warranted. Somero–Tammela is one of the areas in Finland in which complex pegmatites have been found and the first Finnish occurrences of Petalite (Li) and pollucite (Cs) were found from Somero. The Hirvikallio Li-Be (0.2 Mt @ 1.78 LiO_2) and Kietyönmäki Li-Be-Nb-Sn (0.3 Mt @ 1.5% Li) pegmatites are the most important occurrences (Alviola 1989). Two quarried carbonate deposits at Vampula (Huittinen) are dolomitic and there are old calcite rock quarries at Ypäjä and Urjala (Neuvonen 1956). Historically, quartz and feldspar have been important natural resources for the glass industry, which was previously active throughout

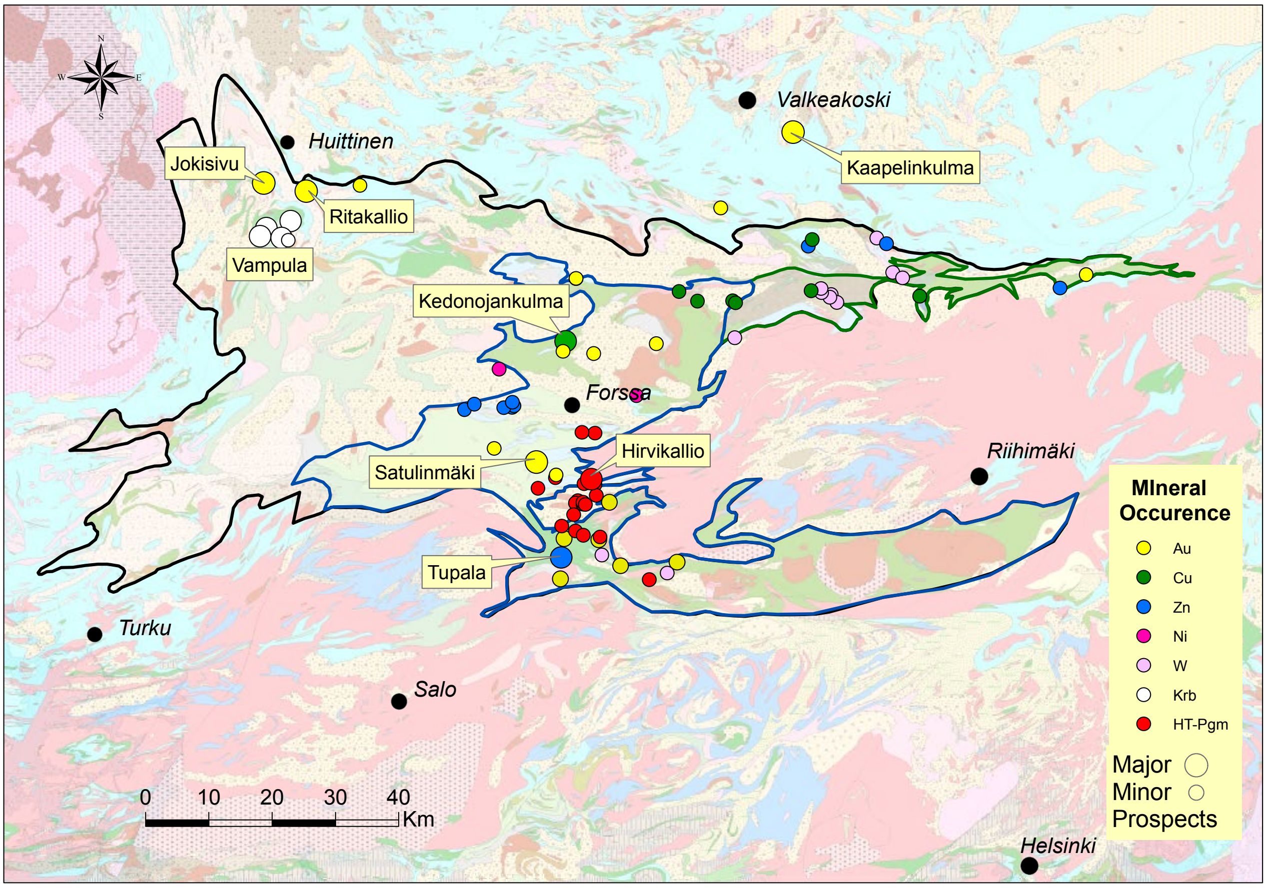

Fig. 2. Mineral occurrences in the Häme Belt. (Bedrock of Finland – DigiKP).

the Humppila–Somero area. Ni-Cu, PGE minerals, ilmenite and apatite have also been found in the Hyvinkää gabbro during the Hyvinkää–Mäntsälä project of the Helsinki University (Kärkkäinen et al. 2000).

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PATTERNS AND PROCESSES: A MINERAL SYSTEMS APPROACH TO EXPLORATION RESEARCH AT GTK

by

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Key issues in research and exploration can be expressed in the form of two iterative questions:

→ What kind of information can we extract from data patterns?
→ Do we need to understand processes to make sense of patterns?

The purpose of this overview is to consider how these questions might be addressed in Finland by implementing a mineral systems approach to mapping and modeling and to present a framework within which the geophysical, geochemical and hyperspectral signatures of hydrothermal and magmatic processes can be related to crustal structure and geodynamic evolution.

BACKGROUND

Concurrent with cyclic changes in demand and prices of commodities, which have always affected the exploration and mining industry over the past two decades, the industry has been facing increasingly demanding regulation and requiremets to become more socially and environmentally responsive and accountable. Further, at the same time as access to land becomes more difficult, the major challenge facing the exploration and mining industry, in locating new resources to replace the already depleted ones, gets gradually more demanding, involving an unavoidable sift of focus to blind but potentially economic resources that may have no obvious surface expression. Targeting based directly upon detection and drilling of geophysical or geochemical anomalies has been effective in locating mineral deposits in the past (including giant buried deposits such as Olympic Dam). However, especially in mature, heavily explored terrain, there wil be, over time, clearly fewer and fewer easily discoverable and yet untested surface expressions of mineralization.

There are two effective responses to this:

- → Improve exploration success through technological development or more intelligent exploration strategies, both in established "brownfields" mining districts and in less mature or emerging "greenfields" terrains.
- → Develop new beneficiation technologies that allow profitable mining of lower grade deposits, or processing pathways that allow cheaper recovery of "new" commodities whose usage is restricted by their presently high prices.

THE MINERAL SYSTEM CONCEPT

The aim of the mineral systems approach is to interpret geophysical and geochemical data within a geological framework based on an analysis of source regions, transport processes and pathways, and depositional mechanisms and sites for metal commodities of interest. The mineral systems concept is derived from the systems approach used systematically in exploration by the petroleum industry.

The mineral systems approach differs from, but does not replace, the more traditional targeting approaches based on the empirical description of deposit types and evaluation of geophysical and geochemical anomalies. Indeed, definition of mineral systems and system tracts can be used to provide a more robust basis for conventional deposit model resource assessment.

The mineral systems concept is best understood in terms of hydrothermal and magmatic processes operating at different scales within a lithological and structural framework, or architecture. A mineral deposit is essentially a chemical anomaly, an efficient mineral system is one in which instabilities and thermal, pressure or chemical gradients favourable to concentration of metals within the system have been maintained for as long as possible.

Thermal gradients for example may be driven by pluton emplacement, as magmatic systems or convective hydrothermal systems in adjacent rocks. Transport of hydrothermal fluids may be tectonically induced during orogenic metamorphism, or may again involve convective flow driven by density and salinity contrasts in porous sedimentary sequences.

The scale, or boundary conditions of the system may vary considerable, as for example signatures of kimberlitic diamond systems could be reflected by deep lithospheric architecture and repeated evidence for alkaline magmatism over time. Systems may also be regarded as closed or open at the scale of interest, as for example the extensive and pervasive albitic and carbonate alteration in supracrustal rocks throughout northern Finland and Norway, from Kuusamo to Kautokeino, which indicate the existence of hydrothermal processes at crustal scale, necessary to upgrade gold from background to mineable concentrations. Likewise the Mount Isa copper system is considered to be the product of synorogenic leaching in a favourable framework of source terrain, permeability, and saline fluid composition. In contrast, the Outokumpu copper system shows no evidence of external sourcing of metals and remained essentially closed system during peak deformation and metamorphism.

MINERAL SYSTEM MAPPING AND MINERAL SYSTEM SIGNATURES

Geochemical and geophysical anomalies represent the integrated sum of all events that affected a mass of rock, in some cases enhancing, or in other cases obscuring and destroying evidenc for mineralization. Therefore it is necessary to extract the event history from an anomalous feature or structure, enabling us to discriminate more effectively between barren and prospective signals. This focus on processes and history allows us to identify the importance and distribution of hydrothermal alteration or magmatic crystallization events that may have left geochemical or redox-sensitive mineral signals, either in potential field or paleomagnetic data. Regional potential field and seismic surveys are already routinely established tools in mapping of poorly exposed terrain and extrapolating structural features to depth. A focus on processes also allows us for the recognition of variation in deposit style, rather than defining a precise group of physical and chemical parameters and debating over whether a particular deposit falls into a specific mineral deposit category.

EXPLORING GEODATA IN MINERAL SYSTEMS – DATA MODELS AND PROCESS MODELS

In recent decades, geoscience organizations, including GTK, have invested considerable effort and resources, in capturing data, and with advances in IT, in developing standardized and validated databases. Platforms and procedures for electronic and remote access, interrogation, retrieval and publication of data are now well established and routinely provided by many organizations. The question remains however, what is the role of geoscience agencies in interpreting the data further, and in providing an array of value-added derivative products?

Systematic analysis of geodata is required to:

- → Improve our understanding of the distribution of the potential mineral resources and to develop a more rigorous understanding of processes controlling mineralization.
- → To develop routine procedures for the analysis and interpretation of geoscience data.
- → To enhance the value of reports and other deliverables to GTK stakeholders and collaborative research groups, firstly within Finland, but later within future projects developed in the Nordic region, and eventually as a way of enhancing contributions to mapping projects and resource assessment in developing countries.

Software for enhanced analysis of geodata has been evolving rapidly in the last two decades. Alongside conventional multivariate statistical techniques, spatially referenced data modeling, or datamining tools have matured and are already widely applied in Finland:

- → GIS-based data modeling in the earth sciences, including weights-of-evidence, fuzzy logic, and neural networks, where prospectivity analysis can be based on comparison with data from analogous terrains (model driven), or be empirically data-driven.
- → Self-organizing maps (SOM), which represent a complementary, unsupervised data mining approach for establishing and visualizing patterns in diverse datasets (SOM output can ideally be used for defining relevant input constraints in GIS analysis).
- → Quantitative pattern detection and classification software.

Numerical simulation of mineralizing processes is another area of research that is being increasingly used to test conceptual targeting of mineral deposit distribution, from regional conceptual studies through to detailed deposit scale structural analysis. This approach is most effective when there is a workflow of successive reiteration between model scenarios and comparison with geologically constrained data.

A STRATEGY FOR IMPLEMENTATION OF MINERAL SYSTEMS STUDIES

It should be stressed that the concepts presented here are an extension of previous approaches and represent an opportunity and mechanism for integrating separate activities, rather than requiring significant reallocation of resources. There have already been a number of projects in Finland that have implicitly used or been directly based on the mineral systems concept, or which have performed systematic data mining, for example in relation to Lapland gold, the GEOMEX Outokumpu study, and some uranium studies.

A workflow and structure is proposed that parallels the industry approach to exploration for mineral resources, typically involving assessment from regional scale area selection, through district scale targeting to prospect definition and delineation.

→ Regional scale terrain synthesis and assessment.
→ District scale assessment of characteristics and controls on mineralization.
→ Patterns of mineralization at deposit scale.

It is therefore reasonable to adopt this scale-dependence in analysis of GTK datasets. The most effective way to demonstrate this is through integration with several existing GTK projects, a strategy which has the following advantages:

→ Fewer resources needed than in establishing new projects.
→ Enhances interpretation and value of reporting.
→ Provides opportunities for undergraduate and post-graduate research projects that can also make use of existing data and train a new generation of exploration-oriented researchers.

Such a research program has both specific as well as more general project deliverables. At a general level, the opportunity exists for integration of the results with the seamless 1: 200 000 geological coverage of Finland, and the recently established regional mineral potential projects in each of the regional units would be ideal places (?) to produce regional scale syntheses that include:

→ Thematic data layers or map sheets of commodity potential, the latter could be based on EUREF mapgrid, which allows Finland being readily subdivided into 10–12 overlapping 1: 200 000 sheets.
→ Regional syntheses (40–80 pages per data layer/mapsheet) providing summary descriptions of geological rock units, event history and nature and distribution of hydrothermal, magmatic and other mineral systems.

KINEMATIC FRAMEWORK OF NEOARCHEAN GOLD MINERALIZATION IN FINLAND – CONSTRAINTS FROM BEDROCK MAPPING AND NUMERICAL SIMULATIONS

by

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Structurally enhanced permeability during orogenic deformation is widely invoked and accepted as a critical factor in the formation of lode gold deposits, driven by feedback between rock material properties and structural architecture, fluid pressure and orientation of far-field stresses. The purpose of this study has been to use numerical simulations of deformation and fluid flow with the commercially available FLAC3D code to test the influence of systematic variations in stress fields and mechanical contrasts between supracrustal rock units and granitoids, based on known structural architectures from the Neoarchean Hattu schist belt in eastern Finland.

The Hattu schist belt has been systematically explored for gold over several decades, as a result of which the Pampalo mine commenced operations during the latter half of 2010. The supracrustal sequence is notable for the relative abundance of felsic volcanic and epiclastic deposits. Isotopic data indicate that deposition, deformation and granitoid intrusion were all very closely related in time, the ages of the earliest supracrustal units, at 2754±6 Ma, effectively overlapping with those of syntectonic granitoids. All exposed contacts between the Hattu schist belt and these granitoids are intrusive, or tectonically modified intrusive contacts, and hence the granitoids cannot represent depositional basement to the greenstone belt. In spite of locally intense and complex deformation, the Hattu schist belt has retained a high degree of stratigraphical coherence, which has enabled the overall topology of its lithic units and structures to be further clarified.

The structural architecture of the Hattu schist belt is characterized by upward-facing, generally steeply dipping structures, and it is possible to establish a close, sequential relationship between tightening of folds, attenuation of fold limbs, development of shear zones with strike-slip displacements, and the propagation of new folds due to strain incompatibilities between the shear zones. Refold interference patterns or attenuation and excision of certain units at outcrop and map scale are therefore more likely to represent progressive deformation of initially upright structures with strain becoming more partitioned within discrete narrow zones. The kinematic histories of these zones suggest the importance of regionally coaxial and vertical constrictional strains, although evidence for more localized local strike-slip deformation is certainly present. Rather than invoking separate deformation episodes, a progressive continuum interpretation is preferred, in which younger structures record the partitioning of deformation into discrete, high-strain zones, with an increasing component of constrictional strain related to continuing granitoid intrusion. Some granitoids intruding the schist belt, such as the Kuittila Suite, form distinct asymmetrical elongate plutons aligned within the structural trend of the schist belt and appear to have been constructed by coalescing steeply dipping *en echelon* sheets intruded during highly partitioned transpressive deformation. Microstructural evidence clearly indicates dynamic recrystallization of alteration assemblages during deformation under upper-greenschist to lower-amphibolite conditions and that the thermal metamorphic peak was synchronous with, or outlasted most of the deformation. The presence of gold mineralization in the syntectonic Kuittila tonalite (2745±10 Ma), and porphyritic tonalite dykes (2723±10 Ma) at the Pampalo Mine, place maximum age constraints on mineralization. Concordant zircon, monazite and titanite ages around 2700 Ma in deformed peraluminous leucogranites are considered to constrain the onset of cooling following post-mineralization metamorphic recrystallization.

Structural controls on alteration and mineralization are a consequence of strain partitioning due to rheological contrasts between rock units and interaction with large scale structures. This is most apparent in the distribution of disseminated mineralization in the hanging wall above the western margin of the Kuittila Tonalite and in the location of the Pampalo gold deposit within the back-rotated toe of a strike slip duplex recording a progressive transition from contractional to oblique extensional behaviour. Numerical simulations of regional structural patterns with FLAC3D are intended to assess the importance of variations in far-field stress configuration in controlling rock failure and localizing mineralization, in particular addressing the issue of whether the inferred kinematics represent a local response to orthogonal shortening and compression, rather than deformation within a regional strike-slip regime.

Models have been systematically run to illustrate the effects of incremental changes in maximum principal stress direction. In particular it is of interest to establish under what, if any conditions, the Pampalo, Hosko and Kuittila structural domains could have been simultaneously active. The results indicate that a NNW−SSE orientation of maximum principal stress could activate the hanging wall setting for the Pampalo gold deposit as a sinistral oblique-slip zone, a prediction which is currently being tested against observations underground and in outcrop. The same stress configuration would however result in reverse sense dip-slip activation in the Kuittila Zone, which would be compatible with gently dipping fractures at a high angle to the tonalite contact.

Given that rock permeability and fluid flow are closely linked to changes in strain rate and orientation within faults and shear zones, it may be possible to estimate time intervals over which structures were actively controlling fluid flow and related mineralization. By attempting to restore displacements along and between shear zones and applying conservative estimates based on both orthogonal convergence and strike-slip deformation rates in modern orogenic settings, it appears plausible that the Pampalo deposit could certainly have formed in less than half a million years.

GEOBOTANY AND BIOGEOCHEMISTRY ACROSS THE TANABELT-GRANULITE TRANSITION ZONE

by

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Geobotany and biogeochemistry are being studied within the context of the green mining concept. Geobotanical prospecting utilizes distribution of plant species indicative of element enrichment in soil, derived from mineralizations. Probably the most famous case in geobotany is the discovery of the Viscaria mine in northern Sweden with the aid of *Silene suecica* (var. *serpentinicola*, formerly *Viscaria alpina*, alpine catchfly). Due to increasing environmental concerns, biogeochemical exploration, involving sampling and chemical analysis of plant tissues (Kovalevsky 1987, Pulkkinen et al. 1989, Dunn 2007, Närhi et al. 2013a), has gained attention within the current green mining thinking. The effectiveness of biogeochemical exploration is based on plant root penetration into soil horizons, often associated with access to groundwater, uptake of nutrients and passive metal accumulation in plant organs (Kabata-Bendias 2001, Dunn 2007). Biogeochemical signatures in plants are associated with multiple processes, such as capillary migration of ions, gaseous transport from oxidizing mineralization, electrochemical transport, decaying litter, and metal-enriched water (Dunn 2007, Närhi et al. 2012). In the case of trees, metals which exceed metabolic requirements are transported to extremities such as bark, leaves, and twig tips.

MATERIALS AND METHODS

We first focused on geobotany, along the Tanabelt-Granulite transect, in Finnish Lapland (Fig. 1), to determine whether there are species present that are indicative of soil fertility, e.g. associated with presence of carbonates. This transition in bedrock composition, (i.e. from mafic rocks of the Tanabelt to felsic granulites) provides geophysically, geochemically and hydrologically contrasting environments for forest composition and diversity of understory plants species (Sutinen et al. 2002, Hyvönen at al. 2003, Närhi et al. 2011). The Lapland Granulite Belt constitutes an edaphic barrier for Norway spruce (*Picea abies*) (Sutinen et al. 2005). Sporadic occurrences of spruce beyond this line exist, such as those on soils e.g. derived from Palloaivi appinite (rich in soil P and Ca) and those at Sarmitunturi, derived from diorites, which all provide necessary site factors (high/moderately high in soil Ca and Mg, low in soil Al) for spruce (Sutinen et al. 2012).

Sites for geobotanical sampling across the mafic-felsic transition (Fig. 1) were randomly selected from the bedrock outcrop database (Geological Survey of Finland), although a buffering constraint was imposed such that sites were located

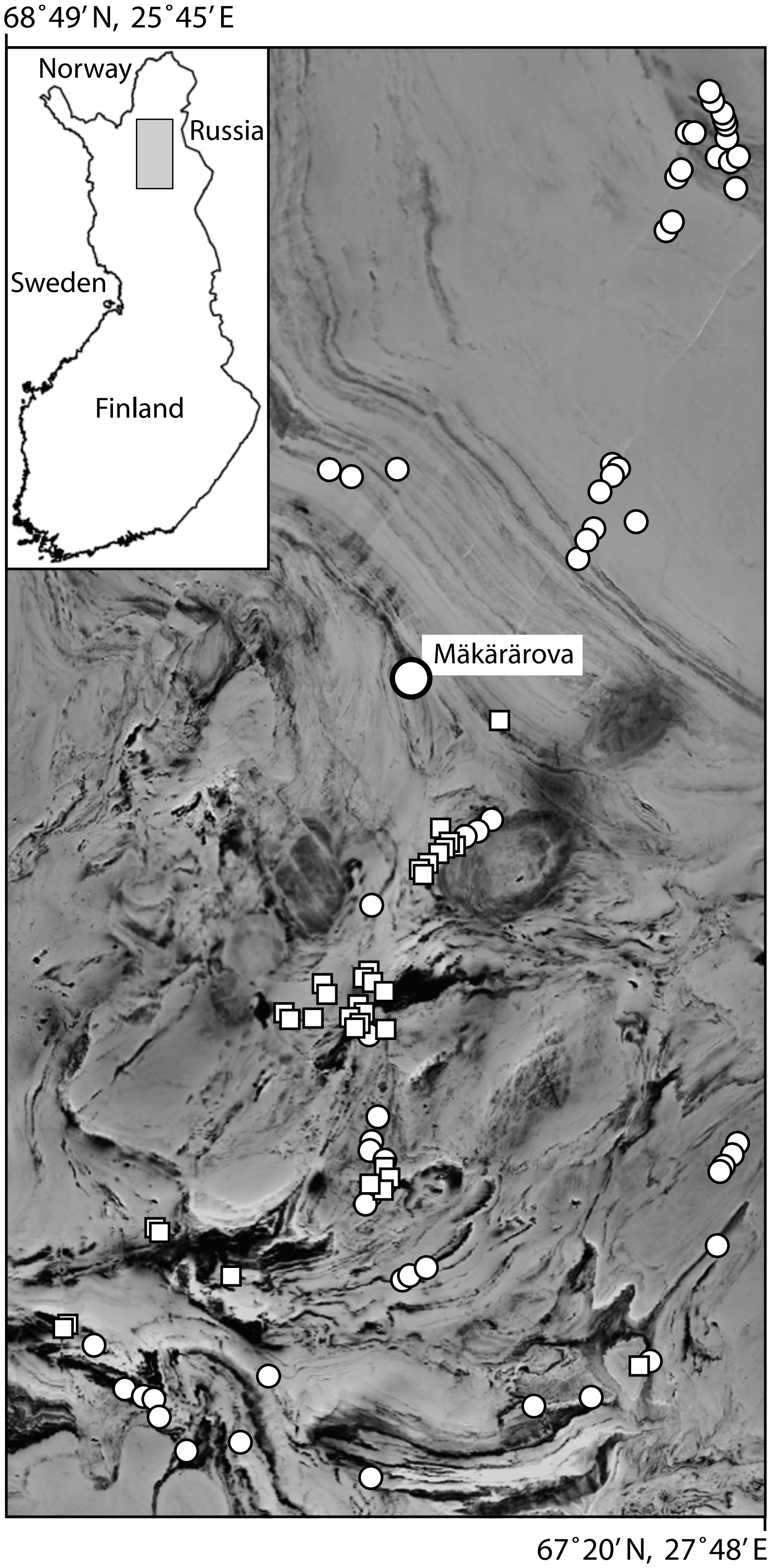

Fig. 1. Felsic (circle) and mafic (square) geobotany study sites and the Mäkärärova biogeochemistry study site on total intensity aeromagnetic map of central Finnish Lapland. (Adopted from Närhi et al. 2011).

>250 m from the nearest road. At 119 sites, plant coverage was analyzed and mineral soil was sampled down to a depth of 20 cm for geochemical analyses of elements extractable with 1 M ammonium acetate (NH_4OAc) at pH 4.5. Samples were sieved to <2 mm fraction and analyzed using inductively coupled plasma atomic emission spectrometry (ICP-AES). Nonmetric multidimensional scaling (NMDS) was applied to analyze the effect of chemical element variations on vegetation composition (Närhi et al. 2011).

We then applied biogeochemistry at Mäkärärova in the Tanabelt (or Tanaelv Belt; centered at 68°11'N and 26°51'E; Fig. 1) bordering the felsic Lapland Granulite Belt (Närhi et al. 2013b). The Tanabelt has been shown to be prospective for Au and REE (Sarapää & Sarala 2011). Common juniper (*Juniperus communis*), thriving on both mafic and felsic terrains, was tested for Au (Pulkkinen et al. 1998, Närhi et al. 2013a) and REE exploration. Biogeochemical field data, including sampling of juniper twigs and the mineral soil B horizon (developed on glacial till and/or sheetwash sediments) as well as determination of juniper coverage and plant species analysis, were acquired in June 2011. The sampling (using 20m point spacing) followed the survey line design previously applied by GTK (Sarapää, pers. comm.; Fig. 2). On the basis of the anomalous Au and REE contents in juniper, drilling of weathered rock was carried out in October 2011.

The Au/REEs were analyzed from juniper twigs, mineral soil (B horizon) and weathered rock sampled down to a depth of 2–10 m. We applied two types of leach procedures (HF & aqua regia) and in determining chemical compositions of the sampled materials. Element concentrations were determined with ICP-AES and

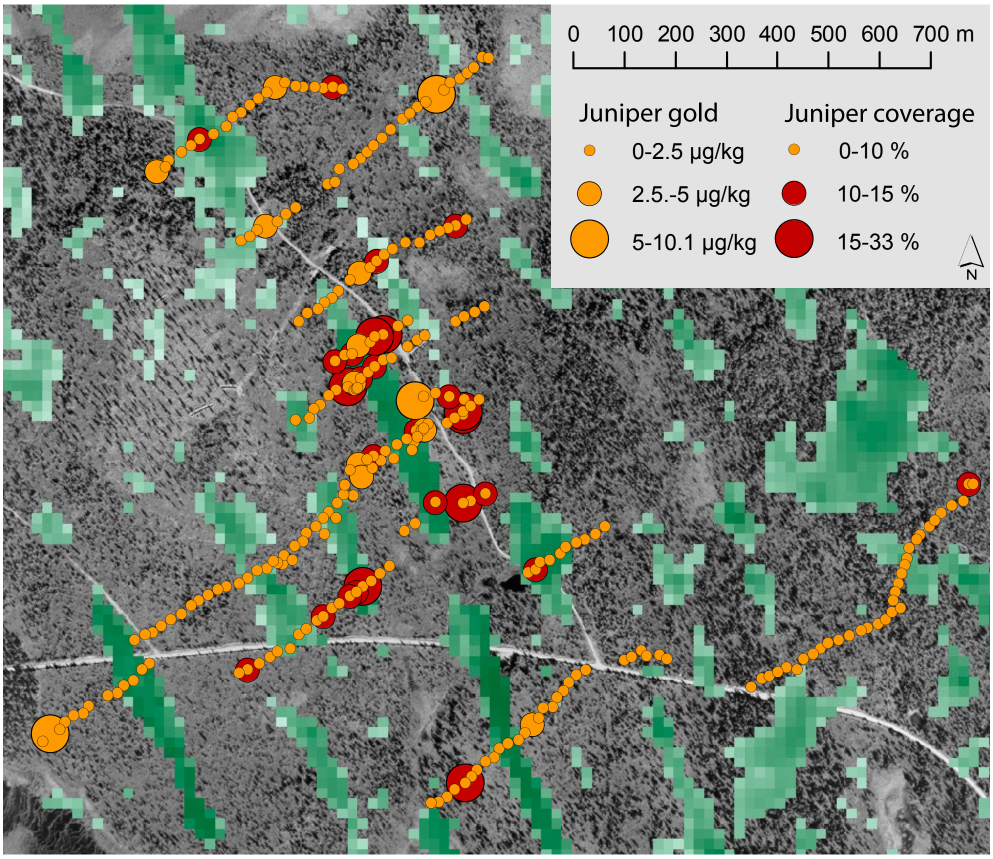

Fig. 2. Mäkärärova survey lines indicated with coverage and Au-concentration of common juniper, plotted on air photo. The green shades represent the hematite prospectivity model by H. Salmirinne at the Geological Survey of Finland. Air photo ©Maanmittauslaitos MLL/VIR/MYY/030/08.

inductively coupled plasma mass spectrometry (ICP-MS). For Au, samples were pre-concentrated using mercury as a collector, and then analyzed with graphite furnace atomic absorption spectrometry (GFAAS). Spearman correlation tests were applied to find dependences between variables of the sampled materials.

RESULTS

Geobotany

Soil Ca concentrations and Ca:Al ratios were found to be the main variables determining forest vegetation composition and diversity along the Tanabelt-Granulite transect (Närhi et al. 2011; Fig. 1). Ca-rich soils are characterised by high Mg concentrations and by low concentrations of Al, S, and Zn. Ca-rich sites, particularly at sites with soil Ca>100 $mgkg^{-1}$, show the highest plant diversities. We found *Geranium sylvaticum* (wood cranesbill) and *Rubus saxatilis* (stone bramble) to be good indicators of Ca-rich soils, and hence important indicator species in carbonate prospecting.

At the Mäkärärova site the spatial pattern of distribution of common juniper coincided with maxima of Au, Ni and Cr concentrations in weathered rock. The highest coverages also spatially coincided with the hematite prospectivity model (Fig. 2). Even if rather sporadic, the distribution of *Luzula pilosa* (Hairy Woodrush) significantly (p<0.001) indicated soil Zn (r_s=0.59) and Ni (r_s=0.5) as well as La (r_s=0.69) in weathered rock. In a similar way distribution of *Trientalis europaea* (arctic starflower) correlated with soil Zn (r_s=0.57), Co (r_s=0.52) as well as La (r_s=0.59) in weathered rock (Närhi et al. 2013b). La in weathered rock was also indicated by the coverage of *Deschampsia flexuosa* (wavy hair-grass) (r_s=0.57) and *Hylocomium splendens* (stair-step moss) (r_s=0.69) (Närhi et al. 2013b). In addition, the distribution of *H. splendens* indicated Zn (r_s=0.59) and Y (r_s=0.59) in weathered rock.

Biogeochemistry

We found Au concentrations of 1-10 μgkg^{-1} accumulated by common juniper at the Mäkärärova site (Närhi et al. 2013b). The sites with anomalous concentrations of juniper La up to 29 $mgkg^{-1}$ and Y 13 $mgkg^{-1}$ were spatially different from those with juniper Au anomalies. The following elements in juniper twigs and soil showed significant (p<0.001) positive correlation: Cu (r_s=0.31), K (r_s=0.44), Mg (r_s=0.31), Mn (r_s=0.44), Ni (r_s=0.44), and Zn (r_s=0.41), whereas correlation of As was negative (r_s=-0.55) between juniper and soil. Even though concentrations of La and Y in juniper twigs behaved in a similar manner (r_s=0.88), no correlation was found in La and Y concentrations between the twigs and the soil. Nevertheless, significant correlations were found between the juniper twig Y and weathered rock Pd(r_s=0.44, p=0.001) as well as between twig La and weathered rock Pd (r_s=0.37, p=0.002) and Pt (r_s=0.33, p=0.005). In addition, juniper As predicted Au (r_s=0.37), Pd (r_s=0.63) and Pt (r_s=0.61) in the weathered rock. The Mn content in juniper predicted La (r_s=0.59), Y (r_s=0.55), Pb (r_s=0.54) and Pd (r_s=0.59) in the weathered rock.

Significant correlation (p<0.001) was found between the soil Th and La (r_s=0.75), possibly indicating the presence of monazite (Närhi et al. 2013b). The soil Th predicted Y (r_s=0.69) and other lanthanides (r_s=0.61–0.76, p<0.001), such as Dy, Er, Gd, Ho, Lu, Nd, Pr and Sm, as well. There were inconsistent patterns between the Au-anomalies from twigs, soils and the weathered rock, yet the sites with highest Au contents (831 and 941 μgkg^{-1}) in weathered rock had high coverage of juniper. Other anomalies in weathered rock that are of prospective interest were Cu up to 1080 $mgKg^{-1}$, Ni 3220 $mgkg^{-1}$, Cr 3100 $mgkg^{-1}$, Pt 286 μgkg^{-1}, La 303 $mgkg^{-1}$ and Y 200 $mgkg^{-1}$, respectively. There was a spatial correspondence between juniper La and Y and weathered rock Cu and Pt, whereas correlation was poor with La and Y and almost non-existent with soil La and Y.

DISCUSSION AND CONCLUSIONS

The Au concentrations in juniper twigs (10 μgkg^{-1}) from Mäkärä were small compared to those (70 μgkg^{-1}) observed by Pulkkinen et al. (1989) at the Pahtavaara Au-mine, and those (50 μgkg^{-1}) by Närhi et al. (2013a) within the Au-prospective Suurikuusikko shear zone at Kittilä. At Mäkärärova the combined data on Au-content and coverage of common juniper is considered to be useful in exploration. A good correlation between soil Th and La and other REEs indicates that regional airborne radiometric data is an effective screening tool for potential lanthanide occurrences. Since gamma-ray flux is attenuated by soil water (Hyvönen et al. 2003), terrains with low soil water content are most suitable for Th/REE exploration. Particularly in cases with dense flight line separation, e.g. 50 m, as at Sokli (GTK radiometric database), target measurements of terrestrial gamma (Hyvönen et al. 2003) would offer an additional advantage in REE exploration.

Juniper is useful in Au-prospecting (Pulkkinen et al. 1989, Närhi et al. 2013a, 2013b), although other conifers may also have potential in mineral exploration (Dunn 2007). Biogeochemical use of spruce and pine, however, is not straightforward because of their different site requirements. Spruce is not a member in the succession sequence in the areas underlain by felsic rock types, particularly the Lapland Granulite Belt (Sutinen et al. 2005). Scots pine (*Pinus silvestris*) is also absent on wet-mesic silty soils derived from mafic rocks of the Lapland Greenstone Belt (Sutinen et al. 2002, Hyvönen et al. 2003, Middleton et al. 2011). Hence more research is needed to explore the use of biogeochemistry and geobotany as part of the green mining concept.

ACKNOWLEDGEMENTS

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THE FORSSA–JOKIOINEN Cu-Au-Zn PROVINCE, WITH SPECIAL EMPHASIS ON THE KEDONOJANKULMA Cu DEPOSIT

by

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INTRODUCTION

The Forssa–Jokioinen ore province, which is located in the volcanic-intrusive Häme Belt, within the central part of the Palaeoproterozoic Southern Finland Supersuite (Fig.1), contains granitoid-hosted Cu and Au occurrences, orogenic Au occurrences and a volcanic-hosted Zn-S occurrence. The area considered here in detail is situated some 10–15 kilometers to the north of the town of Forssa.

The first indications of the ore potential of the area were found as a result of systematic till geochemical exploration in the Forssa–Huittinen area in the years 2003–2005 (Kärkkäinen et al 2012). An ongoing follow-up exploration program to assess the ore potential of the area was initiated in 2004.

Exploration has included till geochemistry, geological mapping, boulder tracing, geophysics and diamond drilling. Target scale geochemistry of the basal till was applied in two phases, reducing the target area and increasing sampling density from 16 samples per one km^2 to 50 meters grid in the most interesting areas. Three targets include till geochemical anomalies of specific suites of elements, namely Cu-Au-Ag-As-Sb(-Te) at Kedonojankulma, Cu-Au(-Te) at Arolanmäki and Zn(-Te) at Kuuma, and in each of these cases, bedrock mineralization has subsequently been confirmed by drilling. The Cu-Au mineralization at Kedonojankulma was also observed in outcrop.

The three discoveries represent different types of mineralization, the Kedonojankulma Cu-Au occurrence is of porphyry-type, the Arolanmäki Au occurrence is in a sheared tonalitic granitoid, and the Kuuma Zn occurrence in altered volcanic rocks. All three targets are still insufficiently studied for evaluation of their economic potential. The Kedonojankulma target includes a preliminary mineral resource estimation from the drilled part of the mineralized intrusion. The Arolanmäki gold occurrence has been intersected by two drill holes, but has not been studied or explored further. The Kuuma Zn occurrence is presently an exploration target, where diamond drilling, geophysical studies and the analysis of the drill cores are ongoing.

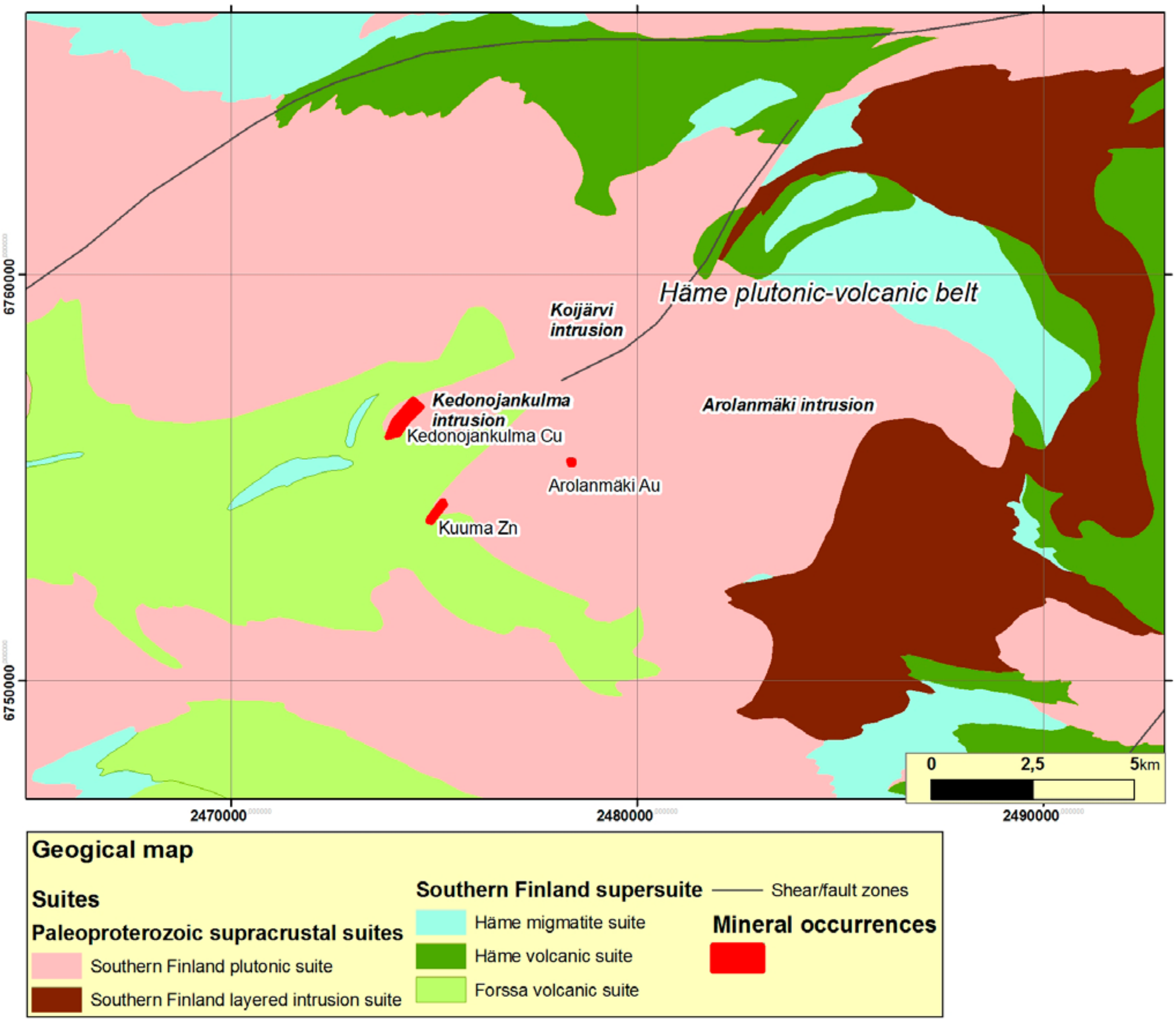

Fig. 1. The location of the Kedonojankulma Cu, Kuuma Zn and Arolanmäki Au occurrences on the Bedrock of Finland – DigiKP regional geological map.

KEDONOJANKULMA Cu OCCURRENCE

The Kedonojankulma Cu-(Au-Ag-Mo) occurrence is the best studied target in the Kuuma-Kedonojankulma-Arolanmäki area (Tiainen et al. 2011, Tiainen et al. 2012). So far, 58 drill holes, totalling 4561 meters drill core, have been drilled within the poorly exposed Kedonojankulma intrusion. The ore resources of the drilled part of the mineralization are 1.8 Mt, including 0.4% Cu, 11 ppm Ag, 0.12 ppm Au and 18 ppm Mo. The occurrence is open at least to depth and the southwest. The area of the drilled mineralization is about 250 x 100 meters, but there are indications that the mineralization could continue several hundred meters further to the south-west near the northern contact of the intrusion (Fig. 2).

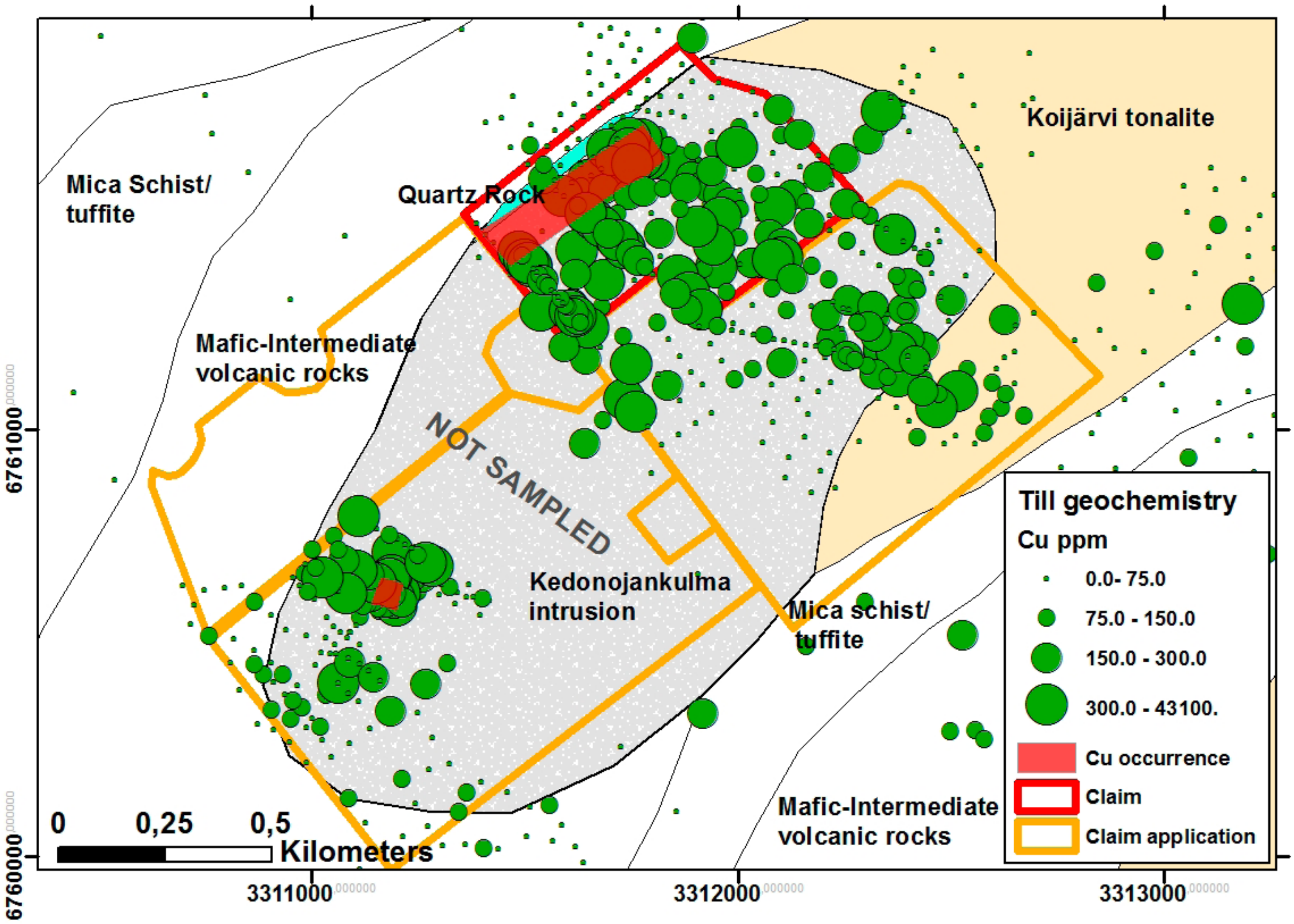

Fig. 2. Kedonojankulma Cu occurrences and Cu content of till in the Kedonojankulma area.

The Kedonojankulma intrusion was mapped as a multiphase tonalitic intrusion, including equigranular and porphyritic tonalite – quartz-plagioclase porphyrite, aplitic veins and mafic veins (Tiainen et al. 2011). The chemical composition of the intrusion plots within the granite-granodiorite field and in geotectonic classification to the field of volcanic arc related granitoids. A possible silicic lithocap in the northern contact of the intrusion indicates that the drilled mineralization is in the upper part of the intrusion and that it was tilted towards the north during the main phase of Svecofennian deformation.

The Cu-Mo mineralization is controlled by hydrothermal fracturing of the intrusion and is related to early silicic alteration. Some of the chalcopyrite has been altered to chalcocite during later supergene alteration by oxidizing fluids. Silver correlates with Cu, occurring both in chalcopyrite and as separate Ag-minerals. Mo forms molybdenite in narrow quartz veins and as patches, typically adjacent to the main Cu mineralization.

The highest Au contents seem to be controlled by later shearing, although anomalous Au contents are also found outside the shear zone. Anomalous Zn has been detected as sphalerite patches in the southern south-western part of the intrusion, outside the main Cu-Mo mineralization.

Petrochemistry

The unmineralized samples from the Kedonojankulma intrusion have peraluminous-metaluminous granodiorite-granite compositions with medium to high-K calc-alkaline character. The Sr/Y ratios are higher than 20 and the (chondrite normalized) REE-patterns show no Eu anomaly with enrichment in LREE and depletion in HREE; e.g. La/Yb ratios are also relatively high (15–27) with less than 2 ppm Yb contents. These geochemical features suggest suppression of plagioclase fractionation and/or relatively oxidizing conditions with high water contents in the parent melt. Thus the Kedonojankulma intrusion shows adakite-like geochemistry, which is a rather common attribute of host rocks to porphyry-copper systems. The Koijärvi and Arolanmaki intrusions adjacent to the Kedonojankulma intrusion share similar geochemical characteristics. Moreover, there also are granitoids in the western and northern parts of the Häme belt which also show petrochemical characteristics comparable with those of the Kedonojankulma intrusion. This suggests that the Häme belt has further potential for porphyry copper type ores.

Mineralized parts (>300 ppm Cu) of the Kedonojankulma intrusion are characterized by elevated SiO2-contents due to silicification associated with the ore forming processes. Mineralizing processes also resulted in slight enrichment in LILE. Parallel with the increasing of copper content of the altered rocks is a pronounced negative Eu anomaly in REE patterns. The post-mineralization, Na-metasomatic alteration under oxidative and alkaline conditions resulted in desilification (decrease of SiO2 content to around 63–65 wt%), and depletion of potassium and barium , as well as enrichment in HREE and development of more pronounced negative Eu anomalies.

Vein systems in the Kedonojankulma intrusion

Detailed vein-system characterization has been carried out on drill core from the Kedonojankulma intrusion in order to better constrain mineralized structures and to understand the importance of superimposing processes on distribution of metals. Six different types of veins were distinguished on the basis of vein mineralogy and texture, considering also the intensity and type of alteration alteration along the veins. In addition to the vein structures, another distinctive peculiarity of the Kedonojankulma intrusion is the occurrence of 0.1–1 m wide shear zones. These shear zones cut and obliterate early Cu- and Mo-bearing veins, whereas late veins cut the shear zones.

The number/meter (abundance) parameters for each type of veins were measured in five drillholes. The results confirm that copper grades correlate well with the abundance of early veins filled by massive dark-grey to black silica and thus sites of pervasive silicification. However, it was also observed that in zones with elevated molybdenium content, the abundance of early veins also increases, although it is always smaller than in the copper rich zones. This suggests that molybdenite precipitated during the early stages of fracture system development and chalcopyrite started to crystallize at more evolved stages of fracture propagation. Abundance parameters for other types of veins do not show correlation with metal contents. High grade gold is associated with certain shear zones in the eastern part of the drilled area. Thus the gold mineralization in the Kedonojankulma intrusion may be attributed to superimposed deformation and does not have genetic association with the formation of the Cu(-Mo) ore.

The vein system of the Kedonojankulma intrusion is not fully comparable with those of Cenozoic porphyry copper systems, the most notable difference being the absence of magnetite in the early veins and the very low abundance of later veins with alteration haloes. However, it should also be considered that current information is available from a relatively small volume (about 250x100x100 m^3) of a presumably much larger porphyry intrusion and outcrop observations indicate that drill holes have only intersected the marginal zone of a more extensive hydrothermal system.

AROLANMÄKI Au OCCURRENCE

The Arolanmäki Au occurrence was found by drilling a slight aeromagnetic anomaly after till geochemistry exploration and boulder tracing. The target is inside the large tonalitic Arolanmäki intrusion. The drilled Au mineralization, including 1.4–1.6 ppm Au in a one meter sample was intersected by two drill holes. Two other one meter samples included 0.1% Cu. At the moment the target awaits further drilling. According to the boulder indications and till geochemistry, the target includes potential for both shear-zone related Au and porphyry type Cu-Au.

KUUMA Zn OCCURRENCE

Kuuma was the first target drilled within the area defined by the primary regional Au-As-Te-Sb geochemical anomaly in the Forssa–Jokioinen area. In addition, a sample submitted by an amateur prospector contained gold within strongly sericitized volcanic rock in a mafic-intermediate-felsic volcanic unit. The target was surveyed by magnetic and IP methods, and drilled during 2005. The 150 meters wide sericitic mineralized zone delineated by the IP survey was subsequently intersected in a drilling profile consisting of four holes. The mineralization included pyrite dissemination and sphalerite-quartz veins in one drill hole. The drilled zinc occurrence, including 1.2% Zn over a one meter interval, was nevertheless outside of this IP anomaly. The Kuuma Zn target was studied later by till geochemistry which indicated continuations to the drilled Zn occurrence. Exploration at the target was resumed in 2012, with a further 11 holes having been drilled in the Zn potential zone. Sphalerite disseminations, sometimes together with pyrite and sometimes alone, were also intersected in felsic-intermediate volcanic rocks. The zinc mineralization is associated with an alteration zone composed of pyrite-sericite schist and garnet-cordierite-anthophyllite rocks. Presently the known mineralized zone is at least 700 m long and about 300 meters wide.

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USING SELF ORGANIZING MAPS IN MINERAL POTENTIAL STUDIES

by

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Self Organizing Maps (SOM) represent a numerical data-driven data mining method for finding correlations and patterns in large data sets, which are too large for a sole human brain to handle. In addition to enabling analyses of ever-increasing amounts of data, data-driven numerical methods reduce the effect of non-objective assumptions that experts often make when analyzing data. However, specialist knowledge, both in mathematical sciences and, in this case, geosciences, is essential in order to obtain reliable results. After all, a computer is just an external memory and power unit connected to human brain.

The theory of SOM, with a number of applications, is thoroughly presented in Kohonen (2001). The method is somewhat identical to neural networks, and is used to iteratively train the model vectors to represent the relationships and patterns within the dataset. The relations can later be used to analyze other, similar datasets. The idea of using SOM in mineral potential studies is to combine geophysical, geochemical and geologic data, and to find possible hidden classes and correlations within the data, which then can be related to areas of high/low prospectivity. The strength of SOM, compared to many other data mining methods, is that the data can be Gaussian or non-Gaussian, categorical or continuous, and sparse or complete in nature. It also can represent either linear or nonlinear relationships. Previously, SOM has been successfully used to analyze geoscience data, but a systematic way of applying the method to mineral prospectivity studies and workflows has not yet been established.

This work, funded by K. H. Renlund foundation and Tekes, is part of a project aiming at establishing a workflow from the initial stage of 1) collecting the observations, through 2) quantitatively analyzing the data, to the stage of 3) deriving the final prospectivity information. In this part of the project, we concentrate on studying the possibilities of using SOM in stage 2. We use data from the Savukoski area in northern Finland. The size of the study area is 35 km x 35 km, and the data set comprises aeromagnetic and aeroelectromagnetic data and till geochemistry. The data is originally point data, which is transformed by interpolation to raster data. Geochemical datapoints are evenly, but sparsely, distributed, and aerogeophysical data is of line-type with line spacing of an order larger than datapoint spacing on a line. Both data types cause challenges in selecting the suitable interpolation algorithm. We use mainly IDW-type interpolation methods with both linear and nonlinear weight functions. For the SOM analysis we use SiroSOM.

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TRACKING CHANGES IN FE-, ZN-, CU-, AND NI- CONCENTRATE FLOWS TO FINLAND, AND ENVIRONMENTAL IMPACTS RELATED TO THEM

by

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Metallic mineral concentrates represent some of the most important classes of commodities in global trade, and the economy of Finland is particularly dependent upon importing metal concentrates. Environmental issues and the quality of governance related to mining and processing in countries exporting concentrates to Finland are of increasing interest and importance when considering the economic and environmental performance of the entire production and supply chain. The main goal of the research reported here is to describe the changes in the material flows related to iron, zinc, copper and nickel concentrates smelted and refined in Finland in the years 2000 and 2010. The other goal is to clarify changes in related waste mineral flows and CO_{2eq} emissions involved in mining, mineral processing and transportation of these concentrates. The Minimization of environmental impacts at mine sites is reflected also by the quality of local governance, which is another aspect to be considered.

Iron concentrates dominate the material flows of metallic concentrates in Finnish foreign trade, and because iron concentrates are not produced domestically, the primary (non-recycled) raw material supply of iron is based entirely on imported concentrates. For other concentrates, the import dependency in 2010 was 90% for copper, 88% for zinc-, and 86% for nickel. The total volume of smelted and refined concentrates decreased between 2000 and 2010, while the share of domestic concentrates increased during the same period. Total CO_{2eq} emissions and the amount of waste minerals related to the concentrates also decreased, as did the CO_{2eq} and waste mineral burden per milled ton, for all concentrates. The environmental performance and governance quality of iron concentrates increased to a very high level, largely as a consequence of a reduction in imports of iron concentrates from Russia. The CO_{2eq} emissions associated with copper concentrates both decreased slightly. For nickel concentrates, environmental performance and governance quality deteriorated during the monitoring period and Finland; both changes are mainly attributable to the increased importance of South Africa as a source of nickel. For zinc concentrates, the situation has remained practically unchanged for ten years.

Possible future changes in environmental impact will most likely be related to copper and nickel concentrates. The waste minerals and CO_{2eq} emissions associated with copper concentrates represent a large part of the total burdens, and changes in circumstances in producer countries, or changes in the distribution of source countries, will potentially have a greater impact on total waste mineral volumes and CO_{2eq} emissions. The share of total impacts due to nickel concentrates is currently relatively low, but an increasing share of domestic concentrates may increase the total environmental impact of nickel in the future, as the new nickel mining capacity is based on open-cut mining of low-grade deposits.

THE KOMATIITE-HOSTED LOMALAMPI PGE-Ni-Cu DEPOSIT AT SODANKYLÄ, NORTHERN FINLAND

by

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The Geological Survey of Finland (GTK) carried out investigations at the Lomalampi PGE-Ni-Cu-Au deposit from 2004–2009. The deposit is located in the municipality of Sodankylä, about 70 km north east from the town of Sodankylä and is hosted by a komatiitic olivine cumulate, which has been assigned to the Peurasuvanto Formation of the Savukoski Group. GTK has drilled a total of 48 holes (6157 m) in the prospect area. In addition to drilling, the area is covered systematically by magnetic and electromagnetic VLF-R ground geophysical surveys., as well as 6 IP and 3 Sampo profiles. No till geochemical surveys were done, but there are two MMI sampling lines, one traverse being across known mineralisation and another further towards the NE.

The PGE-Ni-Cu mineralisation is contained within a 30–60 meters thick, steeply SE dipping olivine orthocumulate body, which has been confirmed by drilling over a strikelength of about 450 m. The current footwall of the cumulate is lithologically heterogeneous, consisting mainly of schistose ultramafic volcanic rocks (komatiites and komatiitic basalts) and subordinate amounts of sulphide- and graphite-bearing phyllites and black schists. A narrow hangingwall sequence composed of black schists and phyllites together with komatiitic volcanics and sills separates the mineralized olivine cumulate from a larger olivine cumulate body to the south-east. The south-eastern cumulate is somewhat thicker than the mineralized cumulate body and, based on interpretation of ground geophysics, extends from 1 to 1.5 km to the NE–SW. The SE-cumulate shows internal differentiation from olivine cumulate to pyroxenitic to gabbroic cumulate along both margins. Although primary magmatic minerals have all been altered, original cumulus textures are commonly discernible; olivine shows rounded, sometimes elongate outlines and has quite variable grain size, from 0.2 to 2 mm.

The mineralized horizon is generally 10–20 meters thick and has been traced along strike for 390 meters. It is generally located at the assumed lower part of the host cumulate, including the schistose/sheared lower contact but can also occur in the middle or even upper parts of the host cumulate. The mineralization consists of disseminated base metal sulphides, mainly pyrrhotite, pentlandite and chalcopyrite (1–6 vol.%). The main platinum phase is sperrylite which is mostly associated with silicates (80%), while Pd occurs predominantly as an unusual Pd-Ni-Te-Sb-Bi phase(s). About 40% of the Pd-phases are associated with sulphides and sulpharsenides. At a 0.1 ppm Pt cut off, the mineralisation has a total tonnage of 3.06 Mt with 0.269 ppm Pt, 0.122 ppm Pd, 0.074 ppm Au, 1682 ppm Ni and 571 ppm Cu.

WHY DO GTK NEED GEOSTANDARDS – GEOSCIML – EARTHRESOURCEML?

by

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INTRODUCTION

It is becoming increasingly important to be able to query and exchange digital geoscientific information between data providers and users (INSPIRE– AuScope - OneGeologyEurope - EGDI – proposal - EURARE etc). Technological opportunities arising from the development of geospatial information standards are making such interoperability a viable proposition. In order to investigate these opportunities a meeting of international geoscience data providers, mainly geological surveys, was held in Edinburgh in 2003. Following from this meeting a working group was established under the auspices of the IUGS Commission for the Management and Application of Geoscience Information (CGI).

The first Interoperability Working Group (IWG) was tasked with developing a conceptual geoscience data model (GeoSciML), mapping this to a common interchange format, and demonstrating the use of this interchange format through the development of a testbed. The second IWG for EarthResourceML (ERML) was established 2010. ERML was developed by the Australian Chief Government Geologists Committee (CCGC) but is now under the governance of the IUGS-CGI. Active participants in the working groups are drawn from BGS (United Kingdom), BRGM (France), CSIRO (Australia), GA (Australia), GSC (Canada), GSV (Australia), APAT (Italy), JGS (Japan), SGU (Sweden), USGS (USA) and GTK (Finland from 2008).

The CGI is continuing to develop GeoSciML and ERML, the markup-up languages allowing the digital exchange of geoscience information locally, continentally and globally. Both the linked global OneGeology project and the European EC project OneGeology-Europe are using GeoSciML to make geological data interoperable and accessible via their web portals. The AuScope portal currently provides access to geological data, including geologic units and mining information based on GeoSciML/ERML from various States, geophysics data from Geoscience Australia, and AuScope's National Virtual Core Library.

GEOSTANDARDS – CURRENT VERSIONS

GeoSciML version 3.0 (http://www.geosciml.org), released in late 2011, is the latest version of the CGI-IUGS Interoperability Working Group geoscience data interchange standard. The new version is a significant upgrade and refactoring of GeoSciML v2 which was released in 2008. GeoSciML v3 has already been adopted by several major international interoperability initiatives, including OneGeology, the EU INSPIRE program, and the US Geoscience Information Network, as their standard data exchange format for geoscience data.).

The GeoSciML v3 data model has been refactored from a single large application schema with many packages, into a number of smaller, but related, application schema modules with individual namespaces. This refactoring allows the use and future development of modules of GeoSciML (eg; GeologicUnit, GeologicStructure, GeologicAge, Borehole) in smaller, more manageable units. The scope of GeoSciML has been extended in version 3.0 to include new models for geomorphological data (a Geomorphology application schema), and for geological specimens, geochronological interpretations, and metadata for geochemical and geochronological analyses (a LaboratoryAnalysis-Specimen application schema).

EarthResourceML v2.0 (ERML) (http://www.earthresourceml.org) is the latest version of the CGI-IUGS Interoperability Working Group earth resource data interchange standard. The CGI-IUGS IWG has worked with INSPIRE to modify the standard to meet EU requirements, and ERML now forms the basis of the INSPIRE Mineral Resources data specification.

ERML can be extended to cover all solid earth resources. It facilitates data transfer and provides a formal structure for reporting resources and reserves that complies with national and international reporting codes. INSPIRE requirements have seen the addition of mineral exploration and environmental aspects, such as mining waste.

GEOSTANDARDS - GTK

GTK´s vision is to be a national geoinformation centre finding ways to make numerical datasets accessible, relevant, and easy to use. Interoperability in Europe due to the INSPIRE directive and global collaboration requires normative conceptual data models, classification systems, and common geological terminology. For this purpose, GTK is moving towards harmonized databases, governed largely by the recommendations of the EU's directives and the technical specifications contained in the emerging data transfer standard – GeoSciML and ERML.

The work at GTK has now proceeded to coherent corporate database structures and digital field data acquisition with uniform classification systems and corresponding lists in fieldPC user interfaces. At a systemic level GTK's bedrock mapping has moved from the traditional map sheet approach to project – based mapping and regular up-dating of a seamless bedrock map database (Bedrock of Finland – DigiKP). The scientific core of Bedrock of Finland – DigiKP is the register of geological bedrock units (Finstrati) – see Fig. 1 centre). Both databases acknowledge international stratigraphic standards and employ IUGS/GCI vocabularies.

The seamless bedrock map (1:200 000) based on the Bedrock of Finland – DigiKP and Finstrati was released online in March 2010 (http://ptrarc.gtk.fi/digikp200/default.html). Development of the bedrock databases will continue in international collaboration on data models and exchange formats due to increasing demands for creating data exchange sercives, ultimately at global scale (Fig. 1 – right upper corner).

Currently GTK focuses on mineral occurrence data delivery according to the interoperability schemes. Separate mineral occurrence databases are combined into a single entity based on global standards (GeoSciML-ERML) and classifications. The next step will be the Nordic, European and global viewing and download services, to be developed interactively with specific use cases and the changing needs of the international mining community.

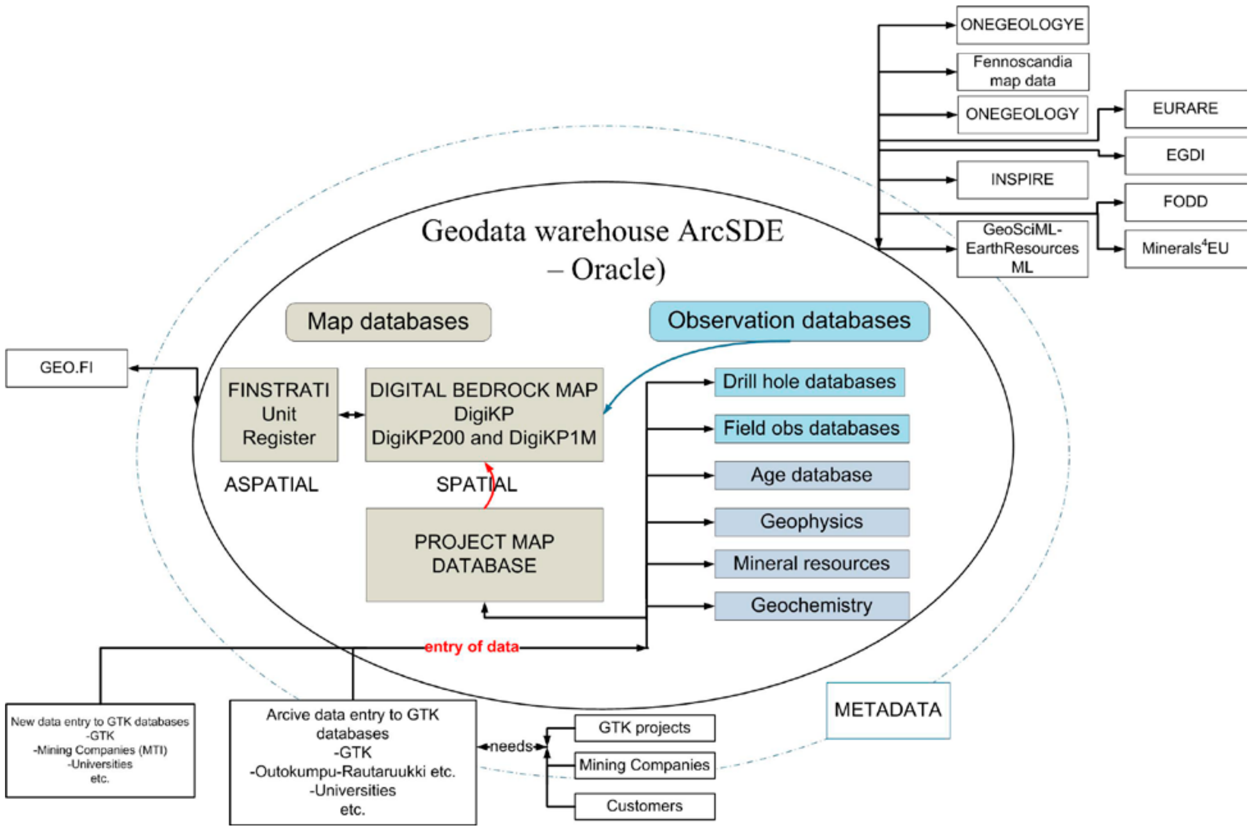

Fig. 1 GTK's bedrock database structure. New data and maps – from archives and fieldwork – will be stored in observation and map databases. These can be used to update the harmonized seamless geology map database and map products to scales of 1:200,000 and 1:1 million that are linked to a non-spatial register of geological units.

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The GTK's Mineral Potential research programme is wide in scope and multidisciplinary in nature. To provide overviews of current research activities within the programme the three day Mineral Potential Workshop was held at Hotel Rauhalahti, Kuopio from 8–10 May 2012. The abstracts of the presentations and posters are published in this GTK Report of Investigation volume.

Altogether 59 scientists participated, and 44 oral and 12 poster presentations were given in nine sessions on mineral raw-materials, material flows and data models, bedrock geology research, isotope geology and mineralogy, ore geology research and exploration methods, numeric and visual modeling and GIS-analysis.

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